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A 50-MEGAWATT ARC HEATER: SCALING PARAMETERS AND PERFORMANCE PREDICTION

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FOREWORD

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ABSTRACT

The Air Force Flight Dynamics Laboratory 50-Megawatt Electrogasdynamics Test Facility is a continuous flow, electric arc heated, hypersonic, wind tunnel for re-entry heat transfer and aerodynamic testing in air. A brief description of arc wind tunnel work at the Laboratory is presented. Arc heater test data up to 5 megawatts of power are presented and problems associated with high-pressure operation of these high-voltage heaters are discussed. The 50-Megawatt Arc Heater design is discussed along with the expected performance of the heater and facility.

This technical documentary report has been reviewed and is approved.

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SYMBOLS

A^*	nozzle throat area, square inches
D^*	nozzle throat diameter, inches
H_0	arc chamber stagnation enthalpy, BTU/lb
I	arc current, amps
MW	arc power V X I, megawatts
N	arc heater scale factor (based on N=1)
P_0	arc chamber stagnation pressure, lb/in^2, unless noted
P_{t_2}	impact pressure behind shock wave, mm Hg
T_0	arc chamber stagnation temperature, $^{\circ}R$
ΔT	cooling water temperature rise, $^{\circ}F$
V	arc voltage, volts
$\dot{W}$	arc heater weight flow, lb/sec
α	flow angularity, degrees
η	arc heating efficiency, percent

INTRODUCTION

The Air Force Flight Dynamics Laboratory 50-Megawatt Electrogasdynamics Test Facility is a continuous flow, electric arc heated, hypersonic, wind tunnel for re-entry heat transfer and aerodynamic testing in air. The direct current, arc air heater is the high-voltage configuration developed by the Linde Company, Indianapolis, Indiana, under contract to the Air Force. The design criteria specificed a heater to operate over a wide range of air enthalpy and pressure with a 50-megawatt power input to the arc. The design of a heater for aerodynamic test purposes is complicated by the requirements for a low contamination of the test flow at a high arc chamber pressure.

EARLY IN-HOUSE ARC HEATER WORK

During 1959, a water-stabilized, carbon arc heater was designed and operated at the Laboratory with limited success. The flow contamination was high and arc stability was poor, making this device useless as an air heater for a hypersonic wind tunnel. Later that year, a small direct arc heater (Figures 1 and 2) was designed and constructed using a tungsten cathode and a water-cooled copper anode. This was a valuable tool to gain experience with arc heating for use with hypersonic wind tunnels. The heater was operated with argon and the test flow was expanded to a hypersonic test flow six inches in diameter. Several basic heater and effluent measurements were made with encouraging results.

The main problem encountered with this direct arc heater as applied to a hypersonic wind tunnel was that it would not heat air without a high contamination of the effluent with electrode material. An inconvenience associated with this heater was that it be taken apart before each run to install a starting fuse.

About the same time, a toroidal arc heater (Figures 3 and 4) was designed utilizing water-colled cooper electrodes with the cathode having a tungsten tip. This arc operated very well with argon and with low pressure air. Power to the heater was kept to below 100 kw with currents up to 500 amps. A 20,000-volt auxiliary starting electrode was used to pre-ionize an air path for the main power to travel. Starting was simple, but heater air pressures had to be kept low for acceptable contamination levels. Operation with argon resulted in high secondary current discharges to grounded models located in the test section of the tunnel. Currents as high as 100 amps were measured which caused the thermal destruction (within seconds) of uncooled metallic models and probes.

The Linde Company developed several heaters under contract, (References 1 and 2). One was the argon shielded direct arc heater (Figures 5 and 6). It operates in a manner similar to the above-mentioned direct arc except that about 10 percent of the test flow consisted of a second gas, argon, injected to shield the tungsten cathode from the oxidizing air.

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The arc was drawn through the sonic throat and attached to the supersonic portion of the anode nozzle. The heater operated well at chamber pressures of 50 to 75 psia and contributed greatly to the further understanding of arc wind tunnels. This was the Laboratory's first heater capable of heating the air to moderate enthalpies (3000 BTU/lb) using almost pure air.

However, the aerodynamic quality of the test flow was still less than desired. The throat material eroded away with time causing progressive changes in flow parameters. Needless to say, the arc moving in the supersonic portion of the nozzle caused further disturbances in the flow.

High-Voltage Arc Concept

To meet Air Force requirements for a heater suitable for a hypersonic wind tunnel, the Linde Company designed and built a high-voltage arc heater applying principles developed in Germany for heating methane to produce acetylene. Substantial improvements were made over the German device so that the present high-voltage arc heater would operate satisfactorily with air. The essential heater parts (Figure 7) are a water-cooled, dead-ended tubular anode (rear electrode), a water-cooled cylindrical cathode (front or nozzle electrode), and an enlarged cylindrical chamber connecting the tandem electrodes. A magnetic field coil surrounds the anode to reduce electrode erosion by rotating the arc attachment and fixing its attachment location axially. The anode, cathode, and nozzle are constructed of copper because of its high electrical and thermal conductivity. During operation, dry air is introduced tangentially into the connecting chamber. The dry air then passes in a vortex pattern through the cathode and throat; its vorticity has the effect of rotating the arc attachment end to reduce erosion. In the early experiments, the arc was started by an auxiliary starting electrode that was moved close to the anode to draw the arc back to the cathode. However, "vacuum starts" were found to be least damaging and are now used exclusively.* After ignition, the arc column extends from an area inside the anode to an area in the cathode near the discharge nozzle. The arc position for a given heater geometry and polarity is a function of the air flow rate, air supply pressure, heater pressure, arc current, and magnetic field strength.

*The vacuum starting technique was developed by the authors to avoid the initial splash of molten metal associated with the use of a starting electrode. The heater is evacuated to less than 1 mm Hg (which it normally will be at the start of a hypersonic tunnel run). Voltage is applied to the evacuated heater and a current detector senses the initial flow of current and immediately operates an isolation valve introducing air into the swirl chamber. The current detector can be replaced by a simple fractional-second time-delay device for those cases where there is little chance of a misfire or where the re-evacuation required by a misfire is not inconvenient. This technique greatly extends the life of the rear electrodes and swirl chamber. It has been applied to heaters with atmospheric discharge by covering the discharge end of the nozzle with an "O" ring sealed plate which is held on by vacuum pressure until the heater is fired and pressurized.

Scaling Laws

Development of the high-voltage arc heater included a study of its scaling laws. A basic one-megawatt heater was designated the unity-size heater (N=1) and its performance was compared with that of half-size, quarter-size, and twice-size heaters of similar internal geometry. It was found that operating pressure P_0, efficiency η and effluent air enthalpy H_0 for an N-scale heater are all equal to those of the basic N=1 heater provided the arc current and voltage in the N-scale heater are N times that in the basic heater. Since the law also dictates that the air weight flow per unit area through the nozzle constriction must be the same for each model, it is seen that the flow rate is directly proportional to N^2. It must be understood that these laws are greatly simplified and they appear to apply only to the front electrode and nozzle. It is our experience that the heater behavior depends more strongly on throat diameter than on any other dimension. The parameter changes which occur when the nozzle throat diameter is changed will be shown later.

AFFDL HIGH-VOLTAGE HEATER EXPERIENCE AND APPLICATION TO 50-MW DESIGN

An N-1 heater was acquired in 1961 and was installed in the prototype arc facility (Figure 8). Initial operation proved very successful, but the heater was limited to low power (less than 100 kw) by the available power supply. As soon as a new 4-MW silicon diode rectifier power supply was installed, extensive experimenting was begun. A major problem arose when the auxiliary starter melted due to high current surges during arc initiation. Shortening the retraction time of this starting electrode was not very successful. A 20,000-volt spark ignition coil (same as the one used on the direct arc heaters) was then proposed to ionize the air for the initial start. This would have worked but the power supply was not electrically insulated for such high voltage. Several other techniques were used to start the heater while it was attached to the tunnel. Some of them succeeded, but not consistently.

The technique now being used on the N=2 and proposed for N=7 (50 MW) heater is the "vacuum start" technique described in the footnote on Page 2. It was determined that the arc heater would self start if the chamber pressure was lowered to 20 mm Hg or less and and if the power supply voltage (2000 volts) was imposed on the electrodes. After the arc fired, the air had to be introduced immediately or the current would remain extremely high and the arc would become attached to vital heater parts. After manual development of the technique, an automatic starter was built and the rear electrode entrance was redesigned so that the arc could move smoothly into the electrode. This method increased starting reliability to about 97 percent. Before the technique was developed no electrode-heat shield combination had survived more than four starts; a special test of the automatic vacuum starting technique yielded 83 starts in rapid succession before failure.

Operation of this heater on the wind tunnel permitted new flow measurement techniques to be investigated and improved. The effect of the stabilizing vortex on the flow quality in the hypersonic test flow has been investigated. It was felt that the axial velocity of the jet, usually in excess of 9000 ft/sec, is several orders of magnitude greater than the circumferential velocity component of the vortex. It was therefore expected that the vorticity would be rapidly attenuated as the flow expanded.

To confirm this a water-cooled swirl probe (Figure 9) was designed and built for use with the prototype facility and the N=1 arc heater. The probe nose was a 0.375-inch diameter copper hemisphere which had five pressure orifices. Four of these were located at 45 degrees to the probe axis so that two were in the pitch plane and two in the yaw plane. The fifth orifice was at the nose stagnation point. While the probe was moved point by point vertically through the conical flow (Figure 10), the pressures were recorded. The pressures were reduced to flow angles by applying Newtonian flow theory. Results show (Figure 11) that, after expanding through an area ratio of 280:1, the swirl angle is less than 1 degree. This probe is described in detail in Reference 3. In 1961, an N=2 arc heater (Figures 12 and 13) was built and connected to a new A. O. Smith D.C. power supply which has an open circuit of 8000 volts and a nominal operating voltage of 4000 volts at 1000 amps.

Initial operation of the heater began late in 1962 with the major portion of the data being taken in 1963. The tunnel was not completed at this time, so the heater was connected to a large pipe and allowed to exhaust to atmosphere. An automatic starter unit similar to the self starter discussed above was also used. The vacuum for starting the arc was achieved with an "O" ring sealed plate on the nozzle exit and a vacuum pump connection to this plate. The vacuum held the plate in place until the arc was initiated. The plate was allowed to fall free when the arc chamber pressure exceeded the atmospheric pressure.

Data were obtained at a variety of operating conditions and heater configurations as shown in Figures 14 to 16. Arc currents ranged from 300 to 1000 amps with voltages from 1800 to 5300. Design data (up to 4.7 MW) for the N=7 heater were verified by the Laboratory with this N=2 heater; these data indicate that the factor N=7 design is conservative. Most of the data were obtained at a bulk stagnation enthalpy of 1800 to 5000 BTU/lb and agreed with the theory for equilibrium sonic flow (Figure 17). It must be understood that some of these data are affected by nonequilibrium. Problems of intense heating on the insulator heat shield and the electrode seals occurred at chamber pressures above 750 psia. Electrode and insulator design changes were made and the redesigned configuration was tested at 1000 psia chamber pressure and four megawatts without failure. The changes found desirable on the N=2 heater were incorporated in the 50-Megawatt Heater design together with a revised rear electrode. Typical voltage, current, chamber pressure, line pressure, and air weight flow traces are shown in Figure 18. In this run the independent variables (controlled quantities) are the mass flow $\dot{W}$ and the power supply internal impedance, which is not displayed. This test was one designed to determine the upper limit of pressure for this throat size at a current of 800 amperes. The arc was started, stabilized for a few seconds at the lower conditions, then advanced to near blowout in two steps, and then the pressure was raised steadily until the arc blew out at 715 psia. Note the increased arc current fluctuations as the heater pressure is increased.

Figure 19 is a sectioned rear electrode (anode) that failed after 32 minutes of operation at 1.4 to 1.9 megawatts of power to the heater and 450 amps. Note the location of the magnetic coil in relation to the erosion area. The coil magnetic vector was upstream and the air flow in the electrode was counterclockwise looking upstream. Contamination for this run and others was less than 0.1 percent of copper by weight of air flow.

Figure 20 is further evidence of the damping of the swirl during the expansion. This throat was attached to an electrode during a low pressure (200 psia), high-voltage (5000 volts) operation of the N=2 heater. As power was increased, the arc became too long and attached at the junction of the electrode, and the nozzle thereby melted this poorly cooled area. The metal flowed through the nozzle with a swirl action which was quickly attenuated during expansion.

The facility (Figure 21) for the N=2 heater was completed late in 1963 and preliminary calibration was begun using a 7.3-inch, 15-degree apex angle, conical nozzle. A typical survey of the $M_\infty 8$ hypersonic flow is shown in Figure 22. Note the flatness of this pressure survey curve. Based on data obtained by the principal author and presented in Reference 8, a blunted model 3.3 inches in diameter could be tested in this test core. Photos of the flow with and without the probe are shown in Figure 23. The tunnel has been operated at heater powers in excess of four megawatts. The tunnel also has been operated with a 20-inch conical nozzle at powers in excess of four megawatts. This means that a 9-inch blunted model could be tested in this test core.

N=7 ARC HEATER DESIGN

Before presenting the 50-Megawatt (N=7) design, a short description of the test methods used in the 4-Megawatt Facility at the AFFDL is in order. A similar procedure will be applied to the N=7 arc heater during calibration of the 50-Megawatt Facility in 1965. During the 4-megawatt arc heater tests, the air flow rate and arc power were controlled manually while pertinent data were gathered by continuous stripchart and multipoint recorders. The recorded data included arc voltage, arc current, chamber pressure, line pressure, air flow rate, and cooling water temperatures. The stabilization time required for steady temperatures was approximately 20 seconds. The power to the gas was calculated by subtracting the heat flux to the cooling water from the electric power to the heater. The average jet enthalpy was calculated by dividing power to the gas by the air weight-flow rate. The heater efficiency was computed by dividing power transmitted to the gas by power fed to the heater. Data repeated to within ±4 percent on separate runs. Typical run times were 2 to 12 minutes depending on the data required.

The 50-Megawatt Arc Heater (Figure 24) is a scaled-up version of the early high-voltage heater. The design criteria specified a heater to operate over a broad range of air enthalpy and pressure with 50 megawatts of power input to the arc. Typical design data are 1.25-inch nozzle constriction, 9-foot front electrode length, 1750 amps, 29,000 volts, 10 lb/sec air flow, 58 percent efficiency, 29 megawatts power to the air, 2700 BTU/lb average air enthalpy, and 100 atmospheres chamber pressure. Scaling parameters deduced by Linde from tests of the $\frac{1}{4}$-, $\frac{1}{2}$-, 1-, and 2-size heaters were applied to the factor 7 design. Design data were verified up to 4.7 MW as described in the earlier discussion and these data show the design to be somewhat conservative.

An 80 percent silver, 20 percent copper alloy was chosen for the rear electrode (the anode), based on N=1/2 experiments Linde performed for AFFDL (Reference 4). The anode erosion rates for this material were 4 percent of those with the standard electrolytic copper. At the more severe conditions (400 amps), the erosion of the silver-copper was 1 percent of that with electrolytic copper. The front electrode will be hard-drawn OFHC copper and the nozzles will be a zirconium copper alloy because of hot strength requirements in the throat region. It is difficult to estimate electrode life for the N=7, but based on N=2 runs and Linde data on silver-copper it should be approximately 2 hours for arc currents below 2000 amps.

Several new problems arose during the extensive testing of parts of this design on the N=2 heater. Some of these problems and the solutions were covered in the previous discussion. A starting problem still existed in the smaller heater when vacuum starts were attempted. On many occasions, the air injectors protruding into the arc chamber permitted the starting arc to attach there and to burn an air injector thus reducing the air swirl. The obvious solution is to electrically insulate the air injectors from the surrounding grounded metal. This is being done in the N=7 design and will be tested on a smaller heater.

The thermal insulators shielding the electrical insulation of the upstream electrode were to be made of bonded mica. During the N=2 testing, several of these insulators showed signs of cracking from the thermal shock. For the N=7 heater, the thermal insulators therefore will be made from Pyroceram or fused silica whichever proves the better during present testing.

N=7 Arc Heater Performance

Figures 25 to 34 show possible operating conditions for the 50-Megawatt Arc Heater. These curves were scaled from in-house test data. These performance curves do not represent all the conditions obtainable with the N=7 heater, but are only those conditions for which test data could be obtained for scaling. The data points shown on Figures 25 and 26 are typical of all the data for all the basic curves. The limits shown on these basic performance curves are not the heater limits, but only the probable limits of the 50-megawatt power supply and/or air supply. The enthalpy shown is an average; the flow core enthalpy is 30 percent higher. This was verified by calorimeters. Note that the efficiency increases as voltage and mass flow are increased. This is primarily due to the increase of arc length and the ensuing better utilization of the fixed electrode length. It is apparent that the scaled data shown at 2820 amps is in error. The most probable reason for the error is that the pressure correction applied to the air flow meter was incorrect. Probably the wrong pressure gage was read which resulted in an improper correction factor. The air flow rates shown are about 19 percent too high for the 2820 amp-1.835 in. throat.

Figures 35 to 41 are the N=7 summary curves. Figure 35 presents the effect of arc current on the voltage with a fixed air flow rate and nozzle constriction. It may be deduced from this curve that the data for the larger throat sizes are the ones most affected by a current rise.

It is obvious from Figure 36 that arc current has a small effect on chamber pressure, particularly for the larger throat sizes. Efficiency and enthalpy change greatly with the current. The efficiency dropped with increasing current because the lower voltage at increased current resulted in a shorter arc, leaving a longer heat loss area on the cathode downstream of the arc termination. The lower voltage resulting from the higher currents lowers the power to the heater resulting in lower enthalpy for a fixed mass flow.

Enlarging the nozzle throat lowers the arc voltage because of the sharp decrease in heater pressure (Figures 39 and 40). The arc column voltage gradient is known to decrease as the arc air pressure decreases and, in the N=7 case, the voltage and pressure become very small when the heater exit is unconstricted. But, the actual air flow pattern has a cold outer layer due to the vortex. This constricts the arc so that a true unconstricted arc condition will never exist. The nominal current of 2100 amps was chosen for the fixed current curves because it represents the maximum current that the 50-megawatt rectifiers can supply at high voltage (20,000 volts or more). The air enthalpy seems to peak at a particular nozzle constriction. This is due to the trade-off that exists among voltage, air flow, and efficiency. The voltage and therefore power decrease when the nozzle constriction is enlarged and this contributes the most to the decrease in enthalpy. Figure 41 also shows the large increases in heater efficiency as the throat is enlarged. The decrease in pressure with increase in throat diameter diffuses the arc column and lowers its temperatures thus decreasing the radiation losses from the arc. Also, the shortened residence time of the hot air, at the lower pressure, decreases the radiation losses from gas particles.

Table 1 shows an N=2 data point and the same data scaled to N=7. The water flow rate required for the N=7 heater at the condition in Table 1 will be 3280 gallons per minute. The water available for the arc heater and any future magnetoaerodynamic accelerator is 10,000 gallons per minute at 1000 psia pressure. The air supply will pump 10 pounds of air per second at 2500 psia supply pressure. The arc spin coil consists of 252 turns of water-cooled copper tubing carrying up to 1000 amps. The coil is connected to an axial traverser to permit moving the arc attachment location from run to run or even during running, thereby spreading the electrode wear and increasing electrode life.

TABLE 1

A TYPICAL 50-MEGAWATT DATA POINT

	N=2 Actual Data	N=7 Scaled Data
Arc voltage	4360	15,220
Arc current - amps	936	3280
Power to heater - MW	4.08	50.00
Power to air - MW	2.14	26.25
Efficiency - percent	52.2	52.2
Air flow rate - lb/sec	0.511	6.260
Bulk air enthalpy - BTU/lb	3970	3970
Heater chamber pressure - PSIA	550	550
Nozzle throat diameter - inches	0.525	1.835
ΔT cathode water - °F	65	65
Cathode water flow rate - gal/min	172	2105
Cathode-nozzle loss - MW (%)	1.64 (40)	20 (40)
ΔT anode water - °F	25	25
Anode water flow rate - gal/min	72	882
Anode loss - MW (%)	0.264 (6.5)	3.25 (6.5)
ΔT swirl chamber water - °F	14	14
Swirl chamber water flow rate - gal/min	18.0	221
Swirl chamber loss - MW (%)	0.037 (1.0)	0.50 (1.0)
Total heat loss - MW (R)	1.941 (47.5)	23.75 (47.5)

50-MEGAWATT FACILITY DESCRIPTION

The 50-Megawatt Electrogasdynamic Facility will be a conversion of the existing 10-foot transonic wind tunnel system at FDL, Wright-Patterson AFB, Ohio. Most of the tunnel structure and auxiliary equipment is being utilized (Figure 42). The facility will be operational by Spring 1965.

The power supply will consist of specially designed saturable reactor control transformers feeding ignitron tube rectifiers grouped in four modules. The modules can be connected in series, series-parallel, or parallel to give a rated output ranging from 1750 amps at 28,800 volts to 10,000 amps at 3550 volts for continuous operation. Much higher outputs are permissible for shorter operating periods.

Air is supplied to the arc heater at a rate up to 10 lb/sec at a pressure up to 2500 psia. It is heated to enthalpies from 2000 to 14000 BTU/lb. The heated air expands through an axi-symmetric nozzle into the test section to Mach numbers from 6 to 15. Two nozzles will be available. One is a conical nozzle with a 16-degree total opening angle which is sectioned to permit operation with 2-, 3.5-, 5-, 6.5-, and 8-foot exit diameters and which has interchangeable throat sections with throat diameters of 1.25, 1.5, 1.75, 2.25, and 3.5 inches. This conical nozzle will be used for testing aerodynamic heating, pressure distributions and aerodynamic forces. For special aerodynamic testing, a contoured nozzle with a 5.5-foot exit is being built. The arc heater and nozzles are cooled by 5000 gal/min at 2000 psi (or 10,000 gal/min at 1000 psi) of demineralized and de-aerated water. The test flow effuses from the nozzle into an open test section. The test cabin contains the model support system which is structurally isolated to eliminate transmission of vibrations. Models can be injected and retracted from the flow, rolled, and pitched to simulate any flight attitude or a variety of heat inputs. Calibration probes will be provided to spot check the flow properties at any time during testing. The flow is recompressed in a convergent-divergent diffuser of special design for arc heated hypersonic flows (Reference 8). The heat is removed by 20 horizontal rows of plain water-cooled tubes angled at 45 degrees to flow; 14 rows of finned water-cooled tubes; and an additional cooler of 14 vertical rows of finned tubes filled with brine (CaCl solution at -40°F) to get minimum temperatures for maximum vacuum system pumping capability. The air is removed from the tunnel volume by steam ejectors at the rate of 1 million cubic feet per minute for pressures down to 40 microns Hg absolute. After the moisture is removed from the air in a barometric condenser, a centrifugal pump continues the compression to atmospheric exhaust conditions.

Facility Capabilities

The 50-Megawatt Electrogasdynamic Facility fulfills a present need for large diameter continuous test flow simulating the flight environment for aerodynamic heating in the critical range (10 to 1000 BTU/ft^2 -sec). To completely duplicate in a wind tunnel the high altitude hypervelocity conditions of re-entry flight for aerodynamic and heat transfer testing would require at least 10,000 atmospheres and 12,000°K (21,600°R) in the stagnation reservoir. Such supply conditions cannot be provided with presently available technology. However, at the expense of free stream properties, exact stagnation point heating conditions (density, velocity, and temperature) can be produced behind a bow shock wave generated by test models in the flow from arc heated air. The 50-Megawatt Facility is designed to simulate fully the severest portion of aerodynamic heating encountered at speeds ranging from 9500 to 27,000 feet per second and altitudes from 90,000 to 280,000 feet. This environment will permit large-scale and real-time investigations of aerodynamic heating as it affects time-dependent materials, ablation and heat penetration into practical structures or cooling systems. A 2-foot exit diameter nozzle can be used to concentrate the high energy air stream to obtain high heating rates, while an 8-foot nozzle exit will produce a large flow in which full size components can be tested.

Another important function of the 50-Megawatt Facility is aerodynamic testing. Within the current hypersonic flow theories such as the Taylor-Lin Blast Analogy, the nonequilibrium flow from the conical nozzles should give satisfactory data. Blunt bodies, such as lifting re-entry vehicles, cause normal shock waves behind which the air temperature jumps to very high values as chemical energy is released. This energy is redistributed to other molecular and atomic modes so that true stagnation temperature exists at the nose of the vehicle. However, pointed models and future winged-vehicle models require a uniform parallel stream of air with conditions in front of the model close to thermodynamic and chemical equilibrium. At stilling chamber conditions of 1500 psia and 2500 BTU/lb the expansion process to test section conditions should proceed in near equilibrium. A special nozzle has been designed for this process based on the three-dimensional method of characteristics. Corrected for real gas effects and boundary layer growth, this nozzle will generate a nominal Mach number 10 flow.

The estimated performance of this facility and detailed description will be presented in a report currently being prepared for publication. All estimates are based on equilibrium and frozen flow (References 5 and 6). The information presented here is corrected for boundary layer as described in Reference 7. The diffuser geometry and model sizes were determined using data from Reference 8. Briefly, the following table presents estimated test section conditions for all nozzles.

TABLE 2

50-MEGAWATT ELECTROGASDYNAMIC FACILITY PERFORMANCE ESTIMATES

NOZZLES: (a) Conical 8-degree half angle, exit diameters 2, 3.5, 5, 6.5 and 8 feet. (b) Contoured 22.5-degree initial total opening angle, exit diameter 5.5 feet, Mach 10.

CORE FLOW DIAMETER: 1.5 to 5.5 feet

BLUNTED CONE MODEL BASE DIAMETER: (0.67 to 2.6 feet) 8 to 32 inches

STAGNATION CHAMBER PRESSURE: 50 to 2000 psia

STAGNATION CHAMBER TEMPERATURE: 5000 to 15,000°F

AIR WEIGHT FLOW: 1.0 to 10 lb/sec

DYNAMIC PRESSURE: 5 to 600 lb/ft^2

AVERAGE STAGNATION ENTHALPY: 1600 to 12,000 BTU/lb (Bulk)

CORE STAGNATION ENTHALPY: 2000 to 14,600 BTU/lb

STREAM VELOCITY: 9500 to 17,500 ft/sec

DENSITY ALTITUDE: 90,000 to 280,000 ft

MACH NUMBER: 6 to 15

STREAM POWER DENSITY: 1 to 10 megawatts/ft^2

FLIGHT SPEED FOR EQUIVALENT STREAM ENERGY: 9500 to 27,000 ft/sec

CONTAMINATION IN TEST FLOW: Less than 0.1 percent by weight

The future possibilities of this facility include a settling or cooling chamber to lower stagnation temperature to 3000°R.. A new heater will be designed and built to operate at low enthalpy and high pressure (2000 to 3000 psia) for better aerodynamic flow. Work is being done towards the design and fabrication of a small 0.5 megawatt magnetoaerodynamic accelerator for use with a N=1.16 arc heater as a heat source. If this proves to be a feasible approach to increasing the velocity of the test flow, a larger one will be built for the 50-Megawatt Facility. Rough estimates indicate the test flow velocity will approach or exceed escape velocity at very high enthalpies.

Problem Areas

One of the major problems with a test facility of extreme temperature and pressure conditions is accurate flow calibration.

Current instrumentation development includes heat calorimeters of various types, pressure probes, and mass induction probes. It is expected that spectroscopy will be successfully used for the determination of flow properties such as the static temperature in the test section.

The problem of nonequilibrium or frozen flow has been previously identified. It is expected that this facility will contribute significantly to the data of reacting flow systems. As empirical information is generated, appropriate aerodynamic theories will be correlated.

CONCLUSIONS

After considerable testing with a small arc heated wind tunnel, it was concluded that the high-voltage arc heater was the best all-around arc heater for high pressure and high enthalpy. The ease of operation (after certain design problems were overcome) and verification of scaling laws convinced us that the 50-Megawatt Arc Heater should be the high-voltage configuration. The heater is conservatively designed and should allow operation at 65 megawatts. The expected facility performance shows the tremendous range of aerodynamic and heating conditions that can be obtained continuously and simultaneously with large diameter test flows. The facility should be completed in the Spring of 1965 with the calibration beginning with the first operational run.

REFERENCES

1. R. C. Eschenbach and G. M. Skinner, Study of Arc Heaters for a Hypersonic Wind Tunnel, WADD-TR-60-354, Linde Company, Indianapolis, Indiana, May 1960.

2. R. C. Eschenbach and G. M. Skinner, Development of Stable, High Power, High Pressure Arc Air Heaters for a Hypersonic Wind Tunnel, WADD-TR-61-100, Linde Company, Indianapolis, Indiana, July 1961.

3. R. R. Heck and R. T. Smith, Arc Heater Flow Angularity Instrumentation Data Report, Laboratory Internal Report ASRMM-TM-63-15, July 1963.

4. R. J. Sarlitto, R. C. Eschenbach, O. A. Brysen, R. N. Laakaniemi and H. H. Troue, Development of High Enthalpy, High Power Arc Air Heaters, RTD-TDR-63-4055, Linde Co., Indianapolis, Indiana, February 1964.

5. R. J. Whalen, K. Pearce, and S. Samet, Similarity Studies for Dissociating Gases in Hypersonic, Low Density Flow, WADD-TR-60-341, Flight Sciences Inc., Buffalo, New York, September 1960.

6. S. Feldman, Hypersonic Gas Dynamic Charts for Equilibrium Air, AVCO Report, January 1957.

7. A. F. Burke and K. D. Bird, The Use of Conical and Contoured Expansion Nozzles in Hypervelocity Facilities, Cornell Aeronautical Laboratory Report No. 112, Cornell University, Ithaca, New York, July 1962.

8. R. T. Smith, Experimental Studies of High Temperature Hypersonic Diffusers, FDL-TDR-64-4, January 1964.

9. K. K. Yoshikawa and E. D. Katzen, Charts for Air-Flow Properties in Equilibrium and Frozen Flows in Hypervelocity Nozzles," NASA TN-D-693, April 1961.

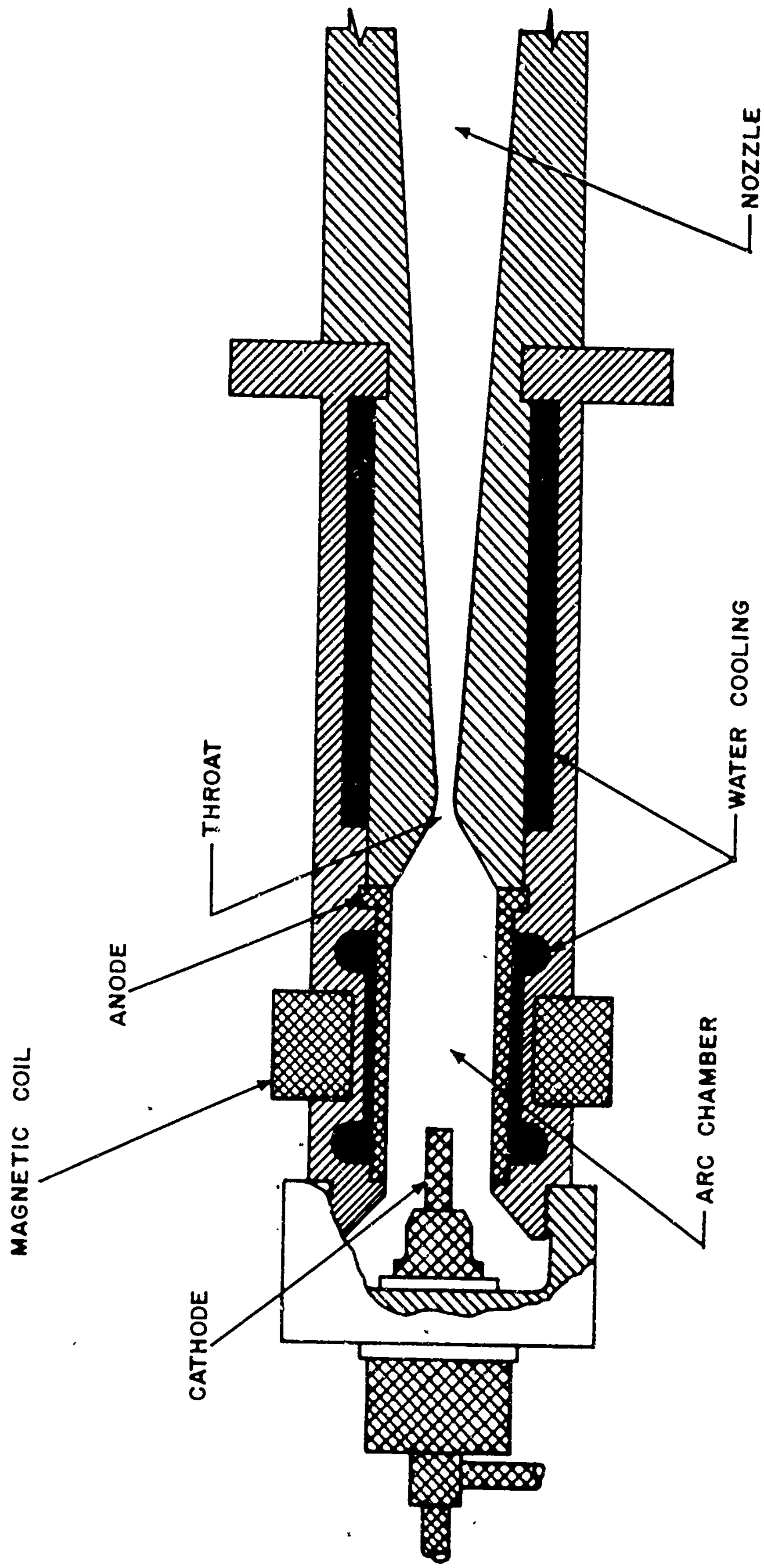


Figure 1. Schematic of Small Direct Arc Argon Heater

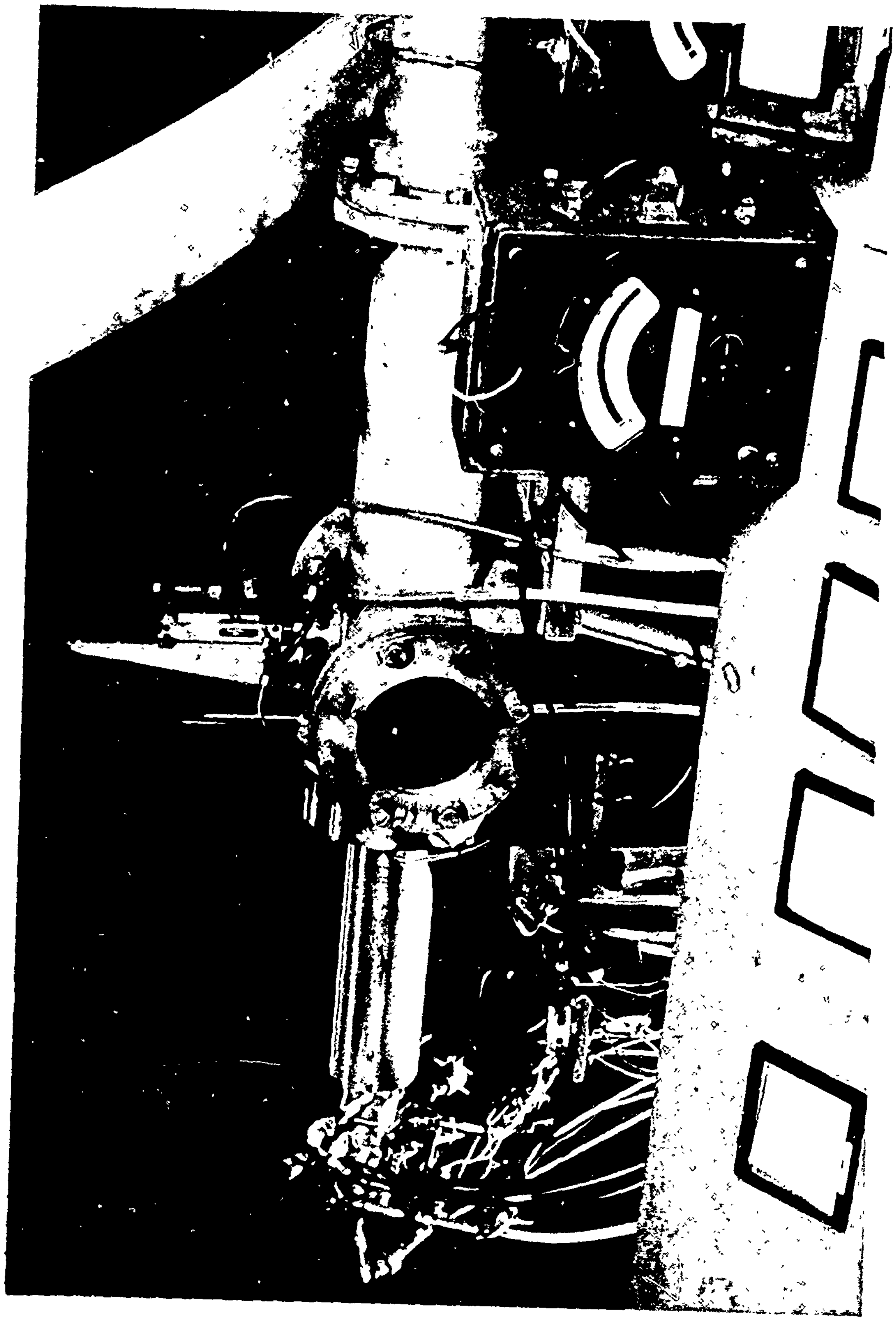


Figure 2. Prototype Hypersonic Tunnel With Direct Arc Argon Heater

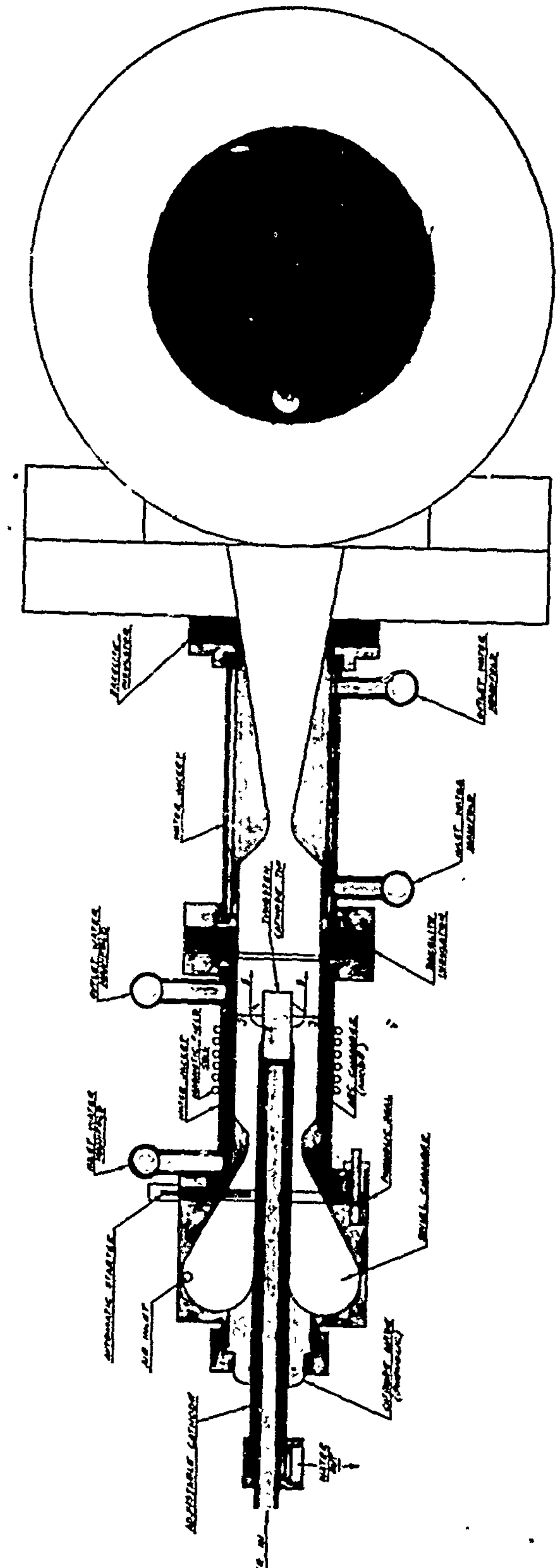


Figure 3. Schematic of Toroidal Arc Air Heater

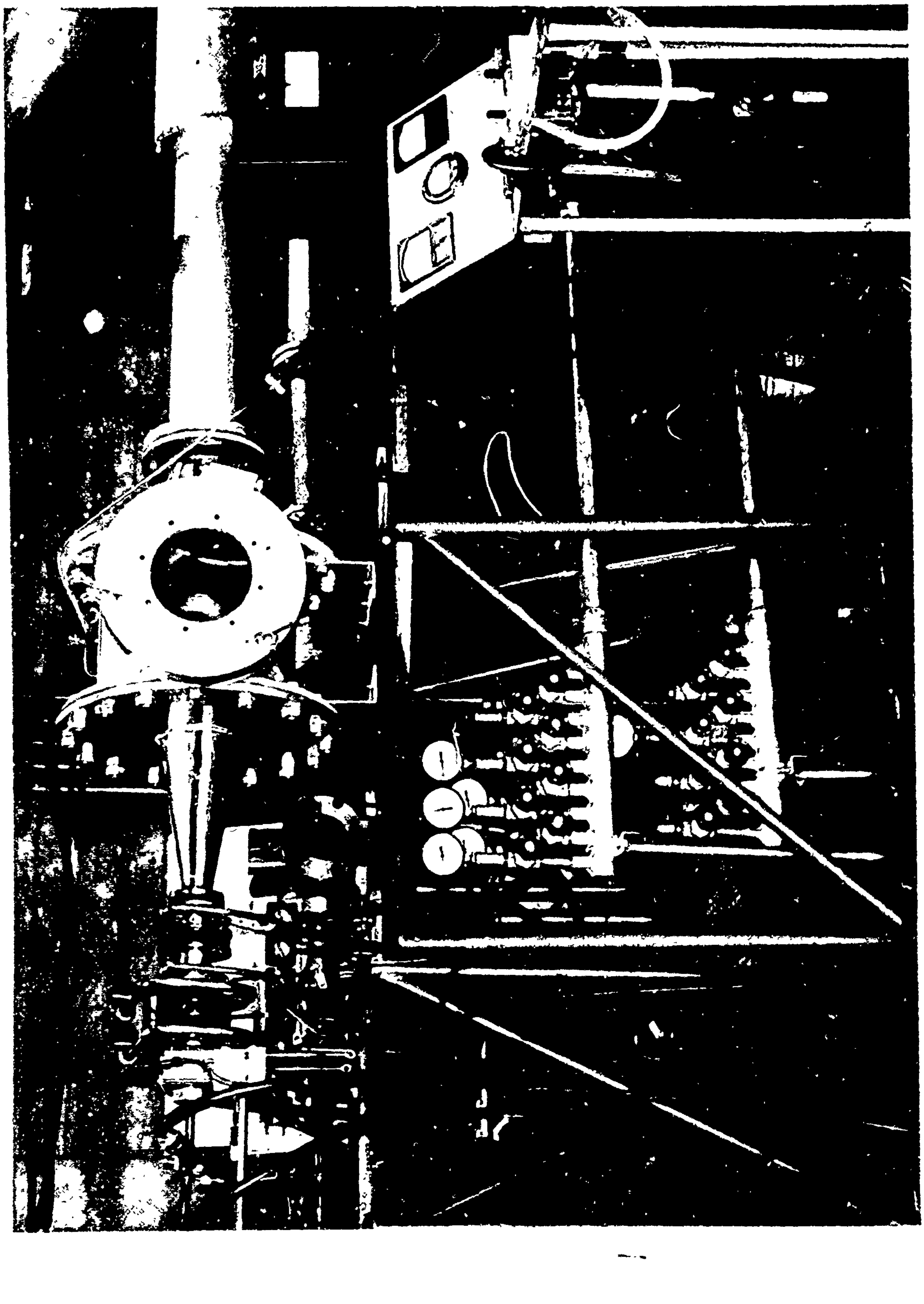


Figure 4. Prototype Low Density Hypersonic Tunnel With Toroidal Arc Air Heater

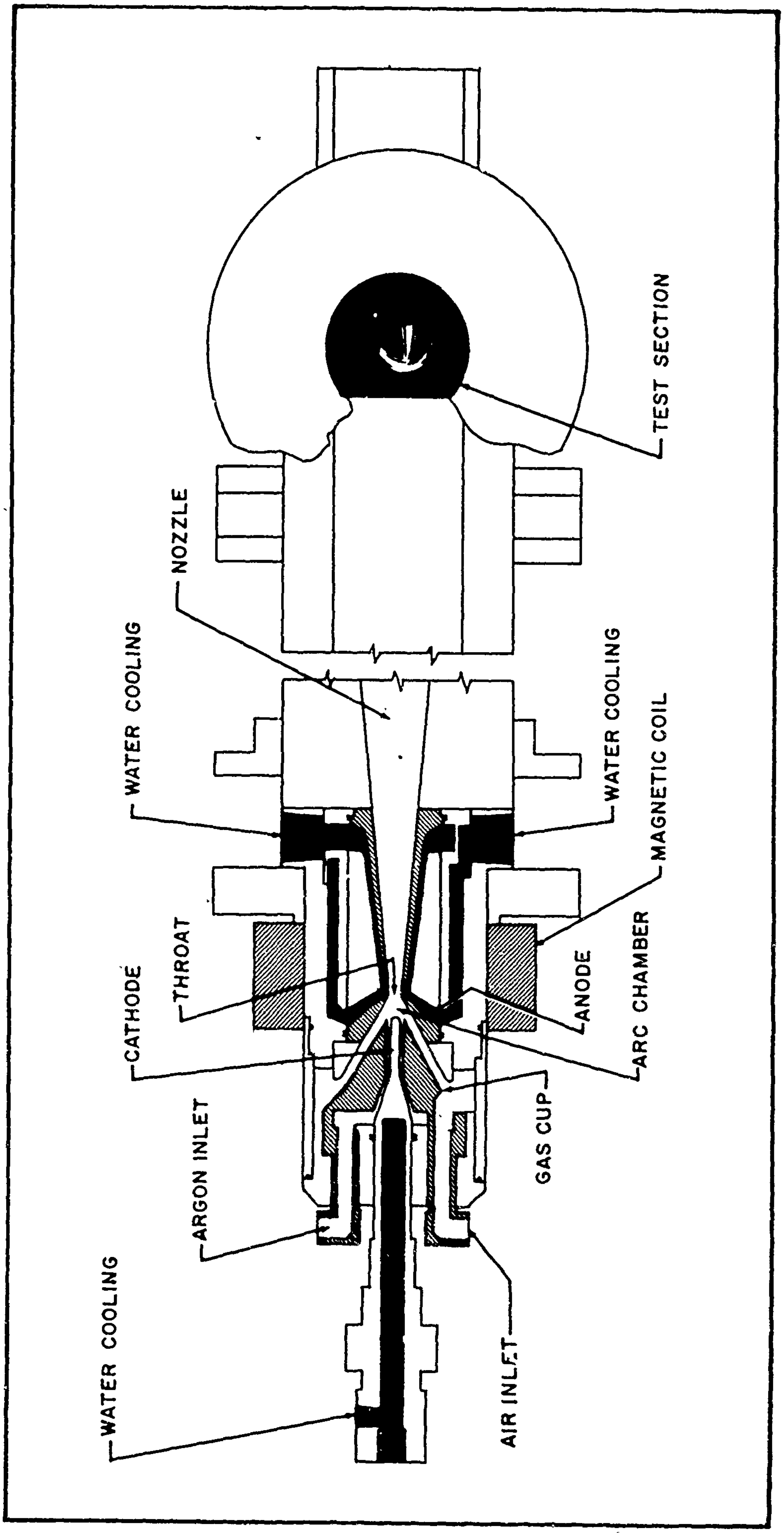


Figure 5. Schematic of Argon Shielded Direct Arc Air Heater

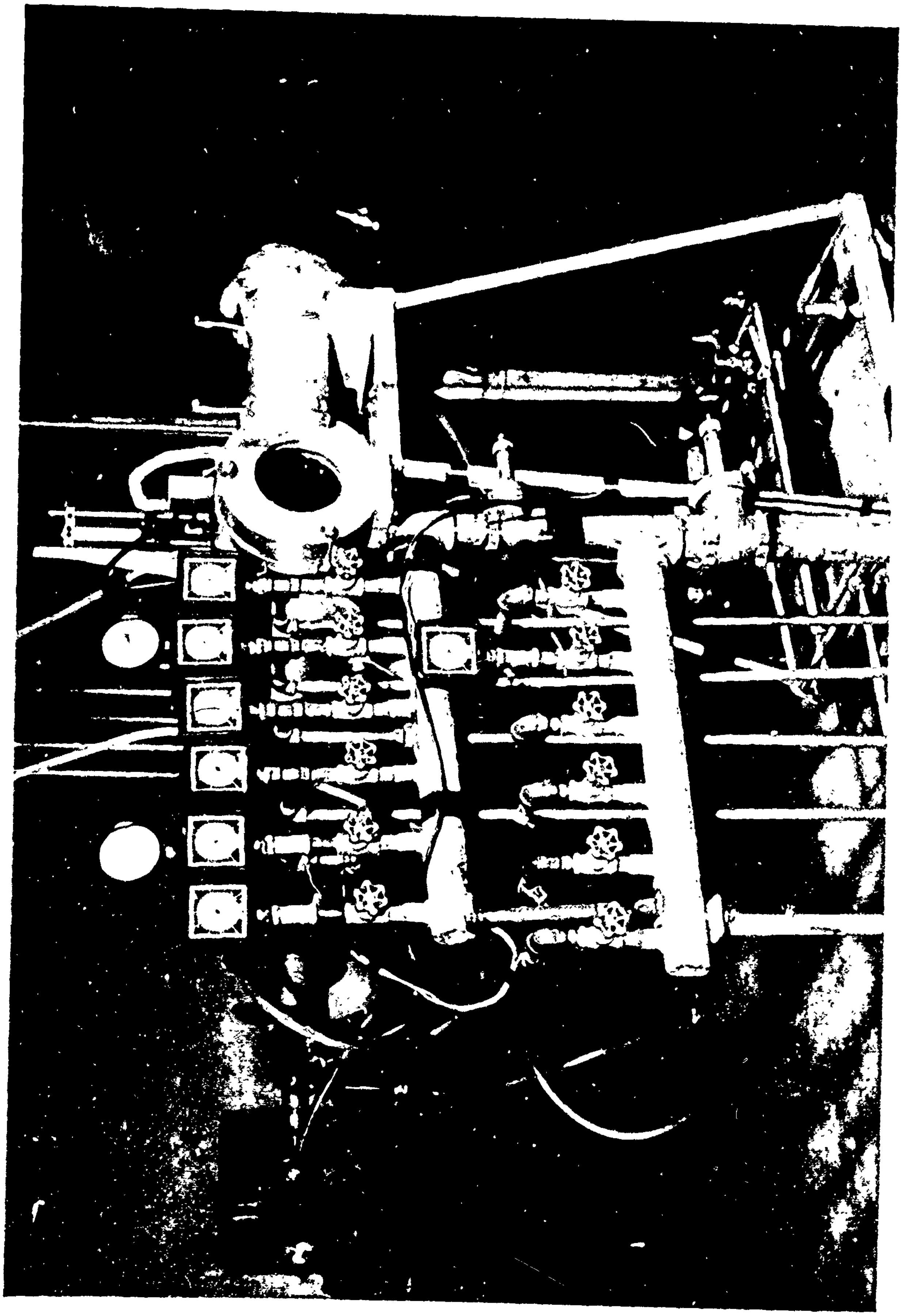


Figure 6. Prototype Hypersonic Tunnel With Argon Shielded Arc Air Heater

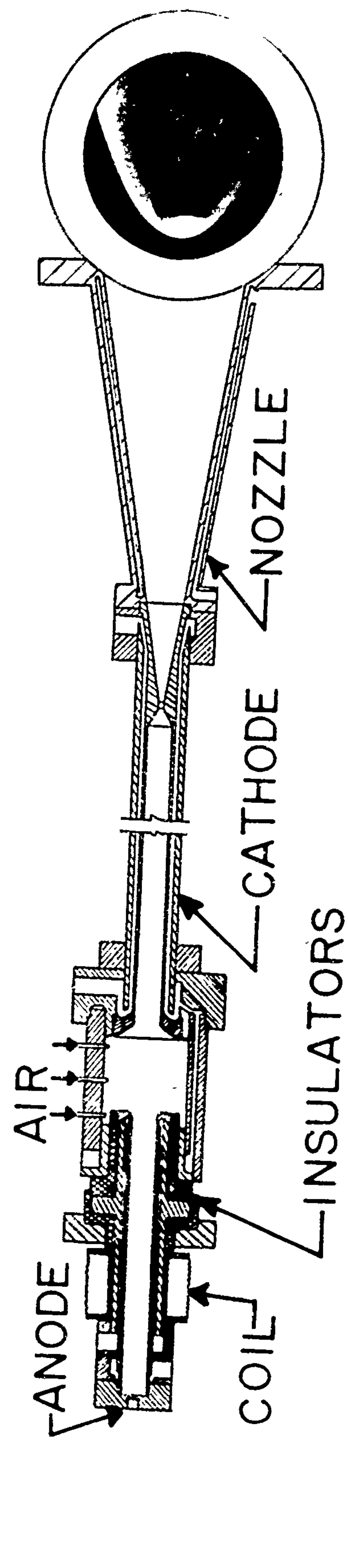


Figure 7. Schematic of Typical High-Voltage Arc Air Heater

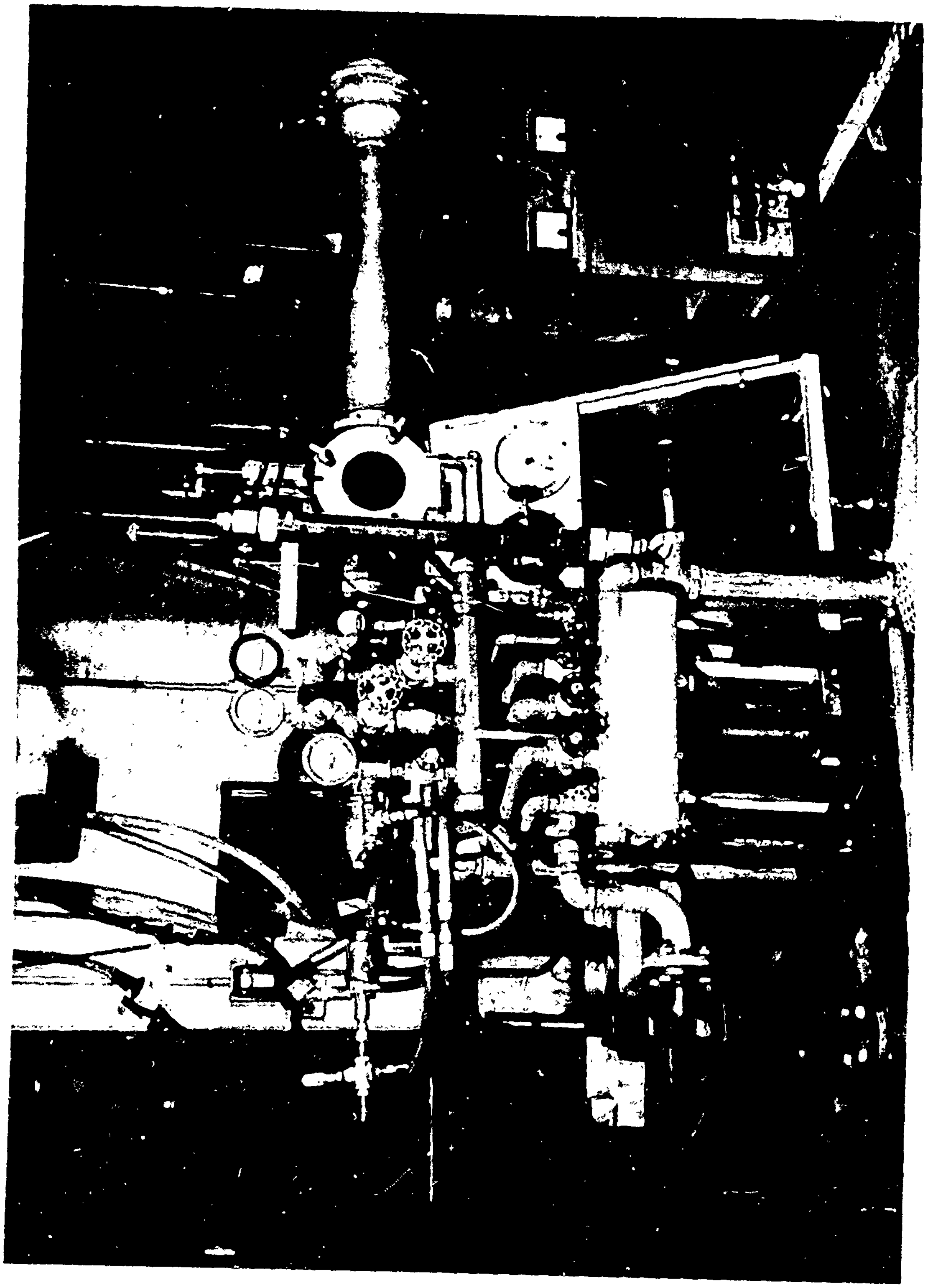


Figure 8. Prototype Hypersonic Tunnel With N=1 High-Voltage Arc Air Heater

Figure 9. Water-Cooled Swirl Probe

Figure 10. Swirl Probe in Prototype Hypersonic Tunnel

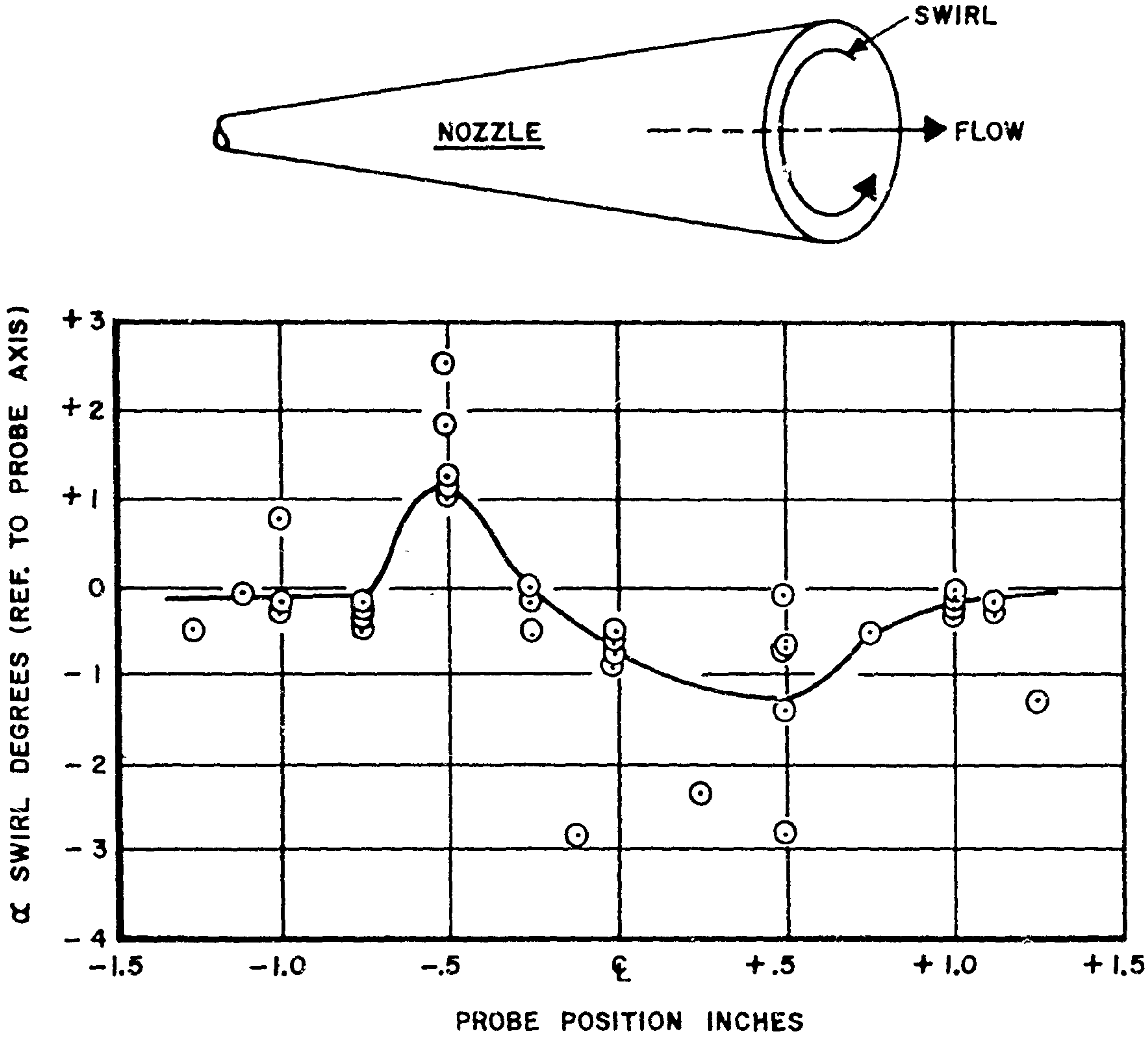


Figure 11. Flow Angularity Due to Swirl

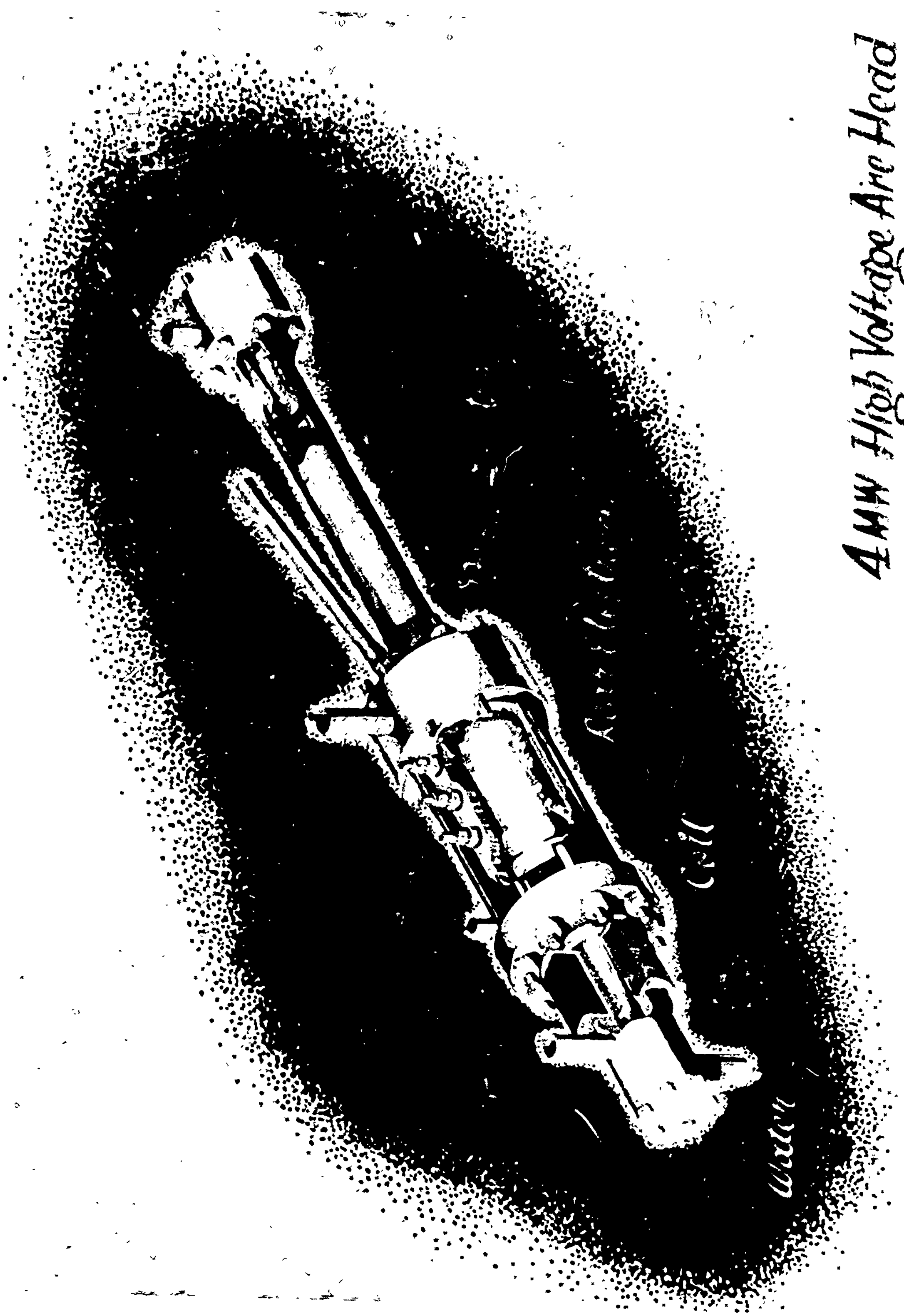


Figure 12. Schematic of N=2 High-Voltage Arc Air Heater

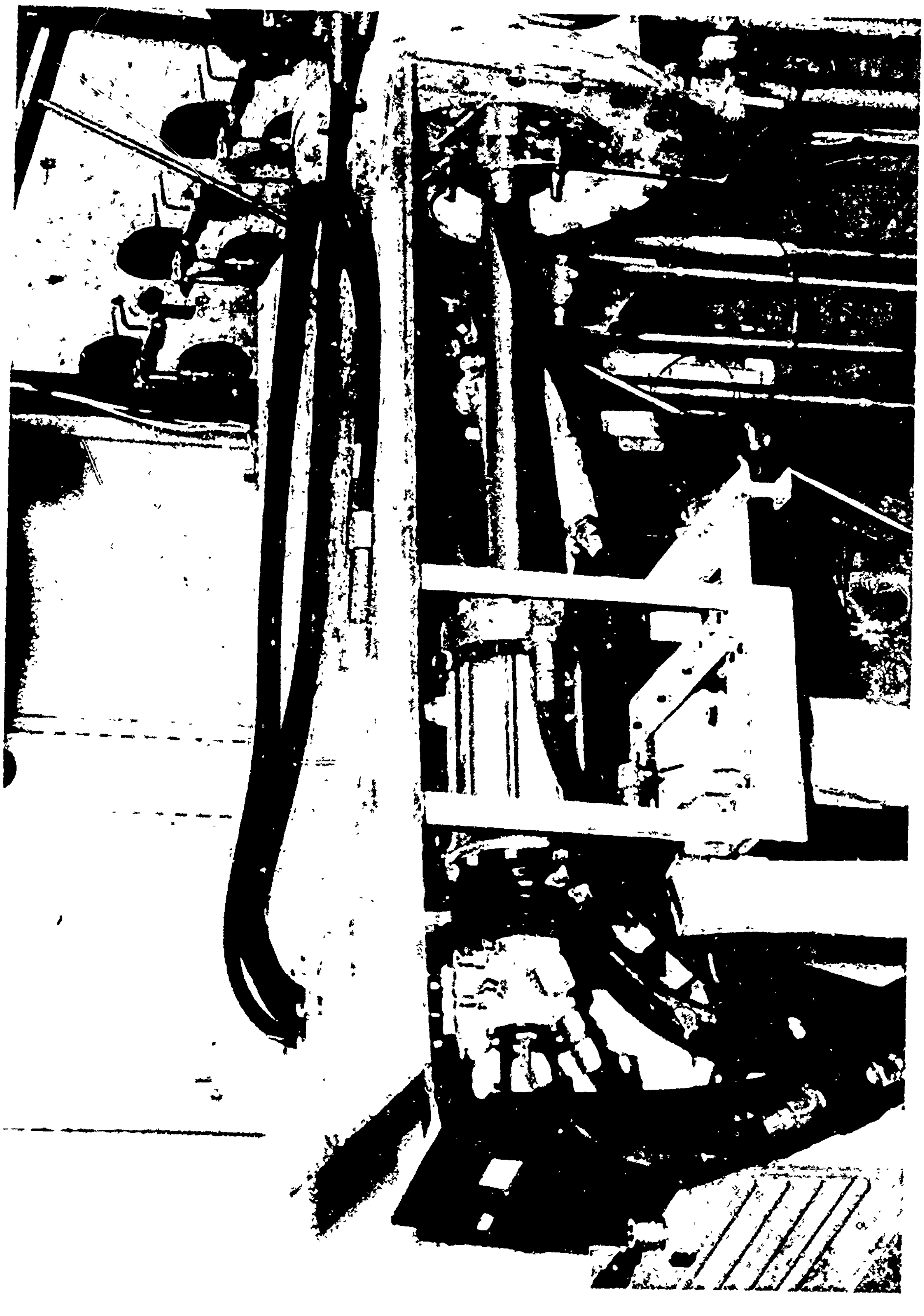


Figure 13. N=2 Heater in Test Rig

N = 2

$D^* = .375$

	⊡	◇	△	X	⬡	SYM.
H_o	1370	2095	2510	3310	2790	BTU/LB
P_o	33.7	42.2	49.0	67.4	62.0	ATM.
$\dot{W}$	.306	.465	.457	.516	.583	LB/SEC
η	33.7	57.4	41.2	46.2	43.6	PERCENT

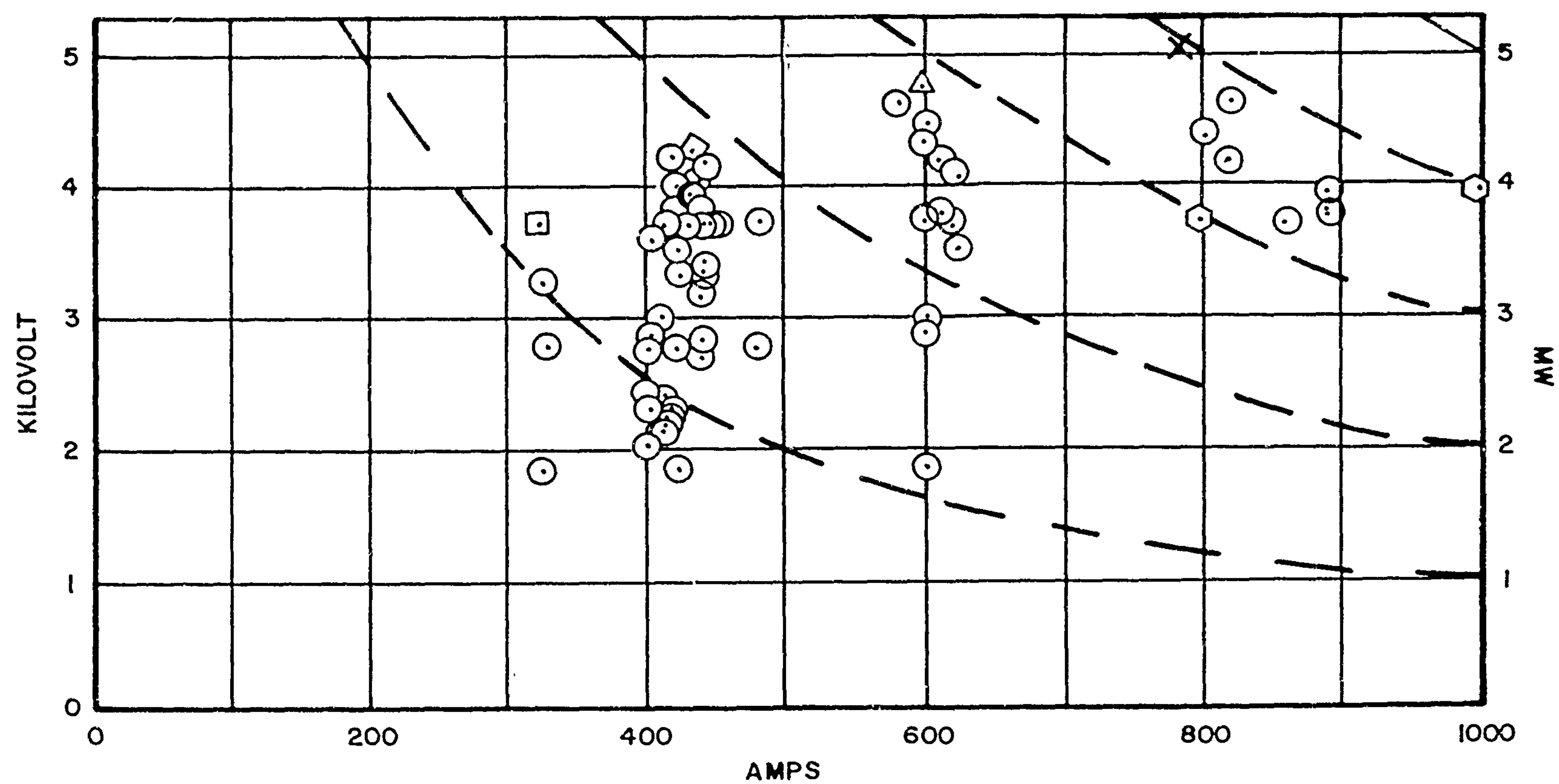


Figure 14. N=2 Data Generated by AFFDL, D* = .375 Inches

N = 2
$D^* = .525$

	⊡	◇	△	◇	SYM.
H_o	2590	3410	2650	3840	BTU/LB
P_o	20.7	25.1	49.0	44.2	ATM.
$\dot{W}$	.392	.426	.862	.592	LB/SEC
η	66.6	63.0	53.9	51.1	PERCENT

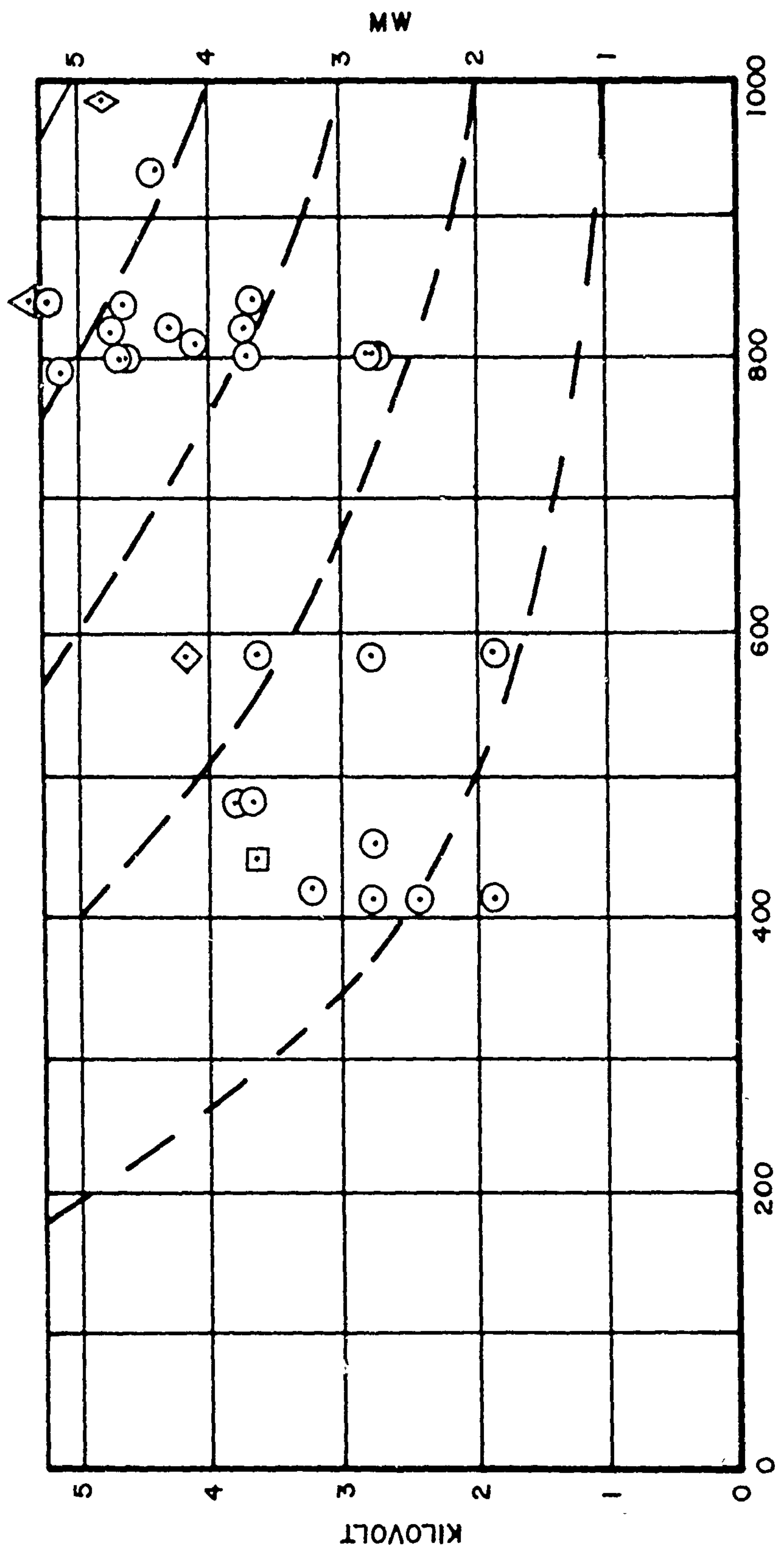


Figure 15. N=2 Data Generated by AFFDL, D* = .525 Inches

N = 2
$D^* = .938$

	◈	△	◊	SYM.
H_o	2340	2940	3840	BTU/LB
P_o	7.3	7.4	15.0	ATM.
$\dot{W}$	.536	.510	.861	LB/SEC
η	72.2	69.5	77.0	PERCENT

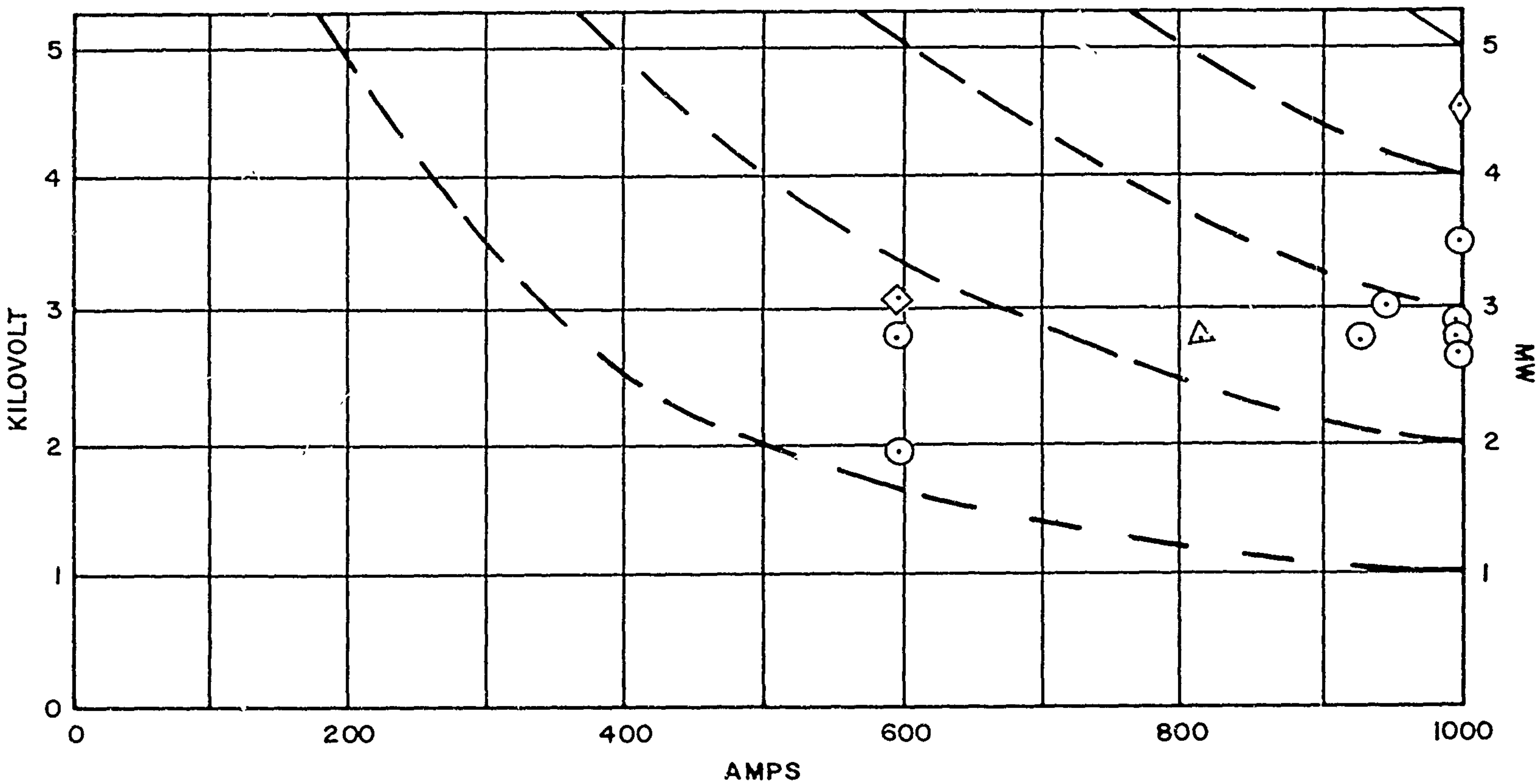


Figure 16. N=2 Data Generated by AFFDL, D* = .938 Inches

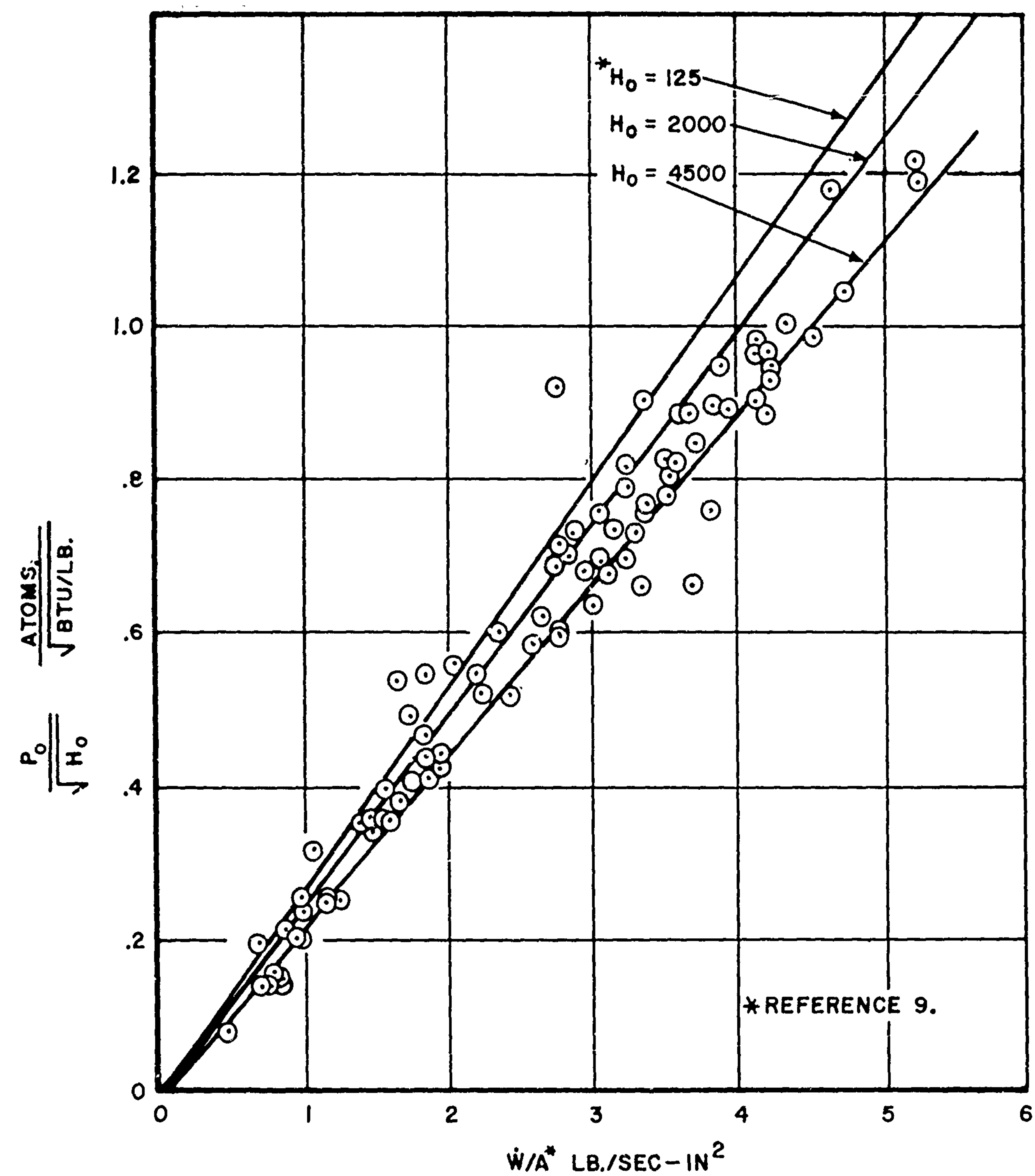


Figure 17. Comparison of Measured and Calculated Pressure - Enthalpy Parameter for Sonic Mass Flux

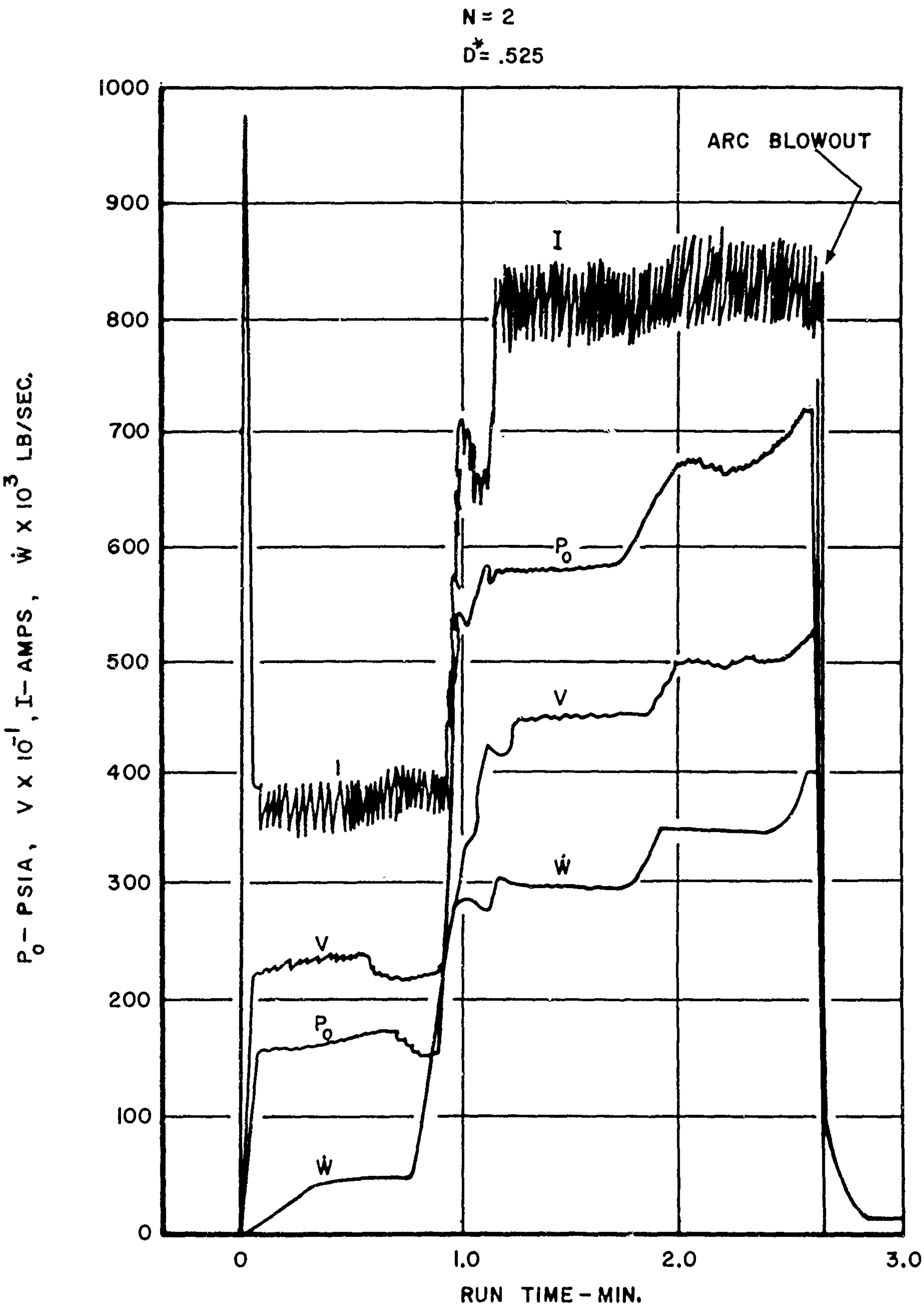


Figure 18. Replot of Typical Voltage, Current, Pressure, and Mass Flow Data, N=2

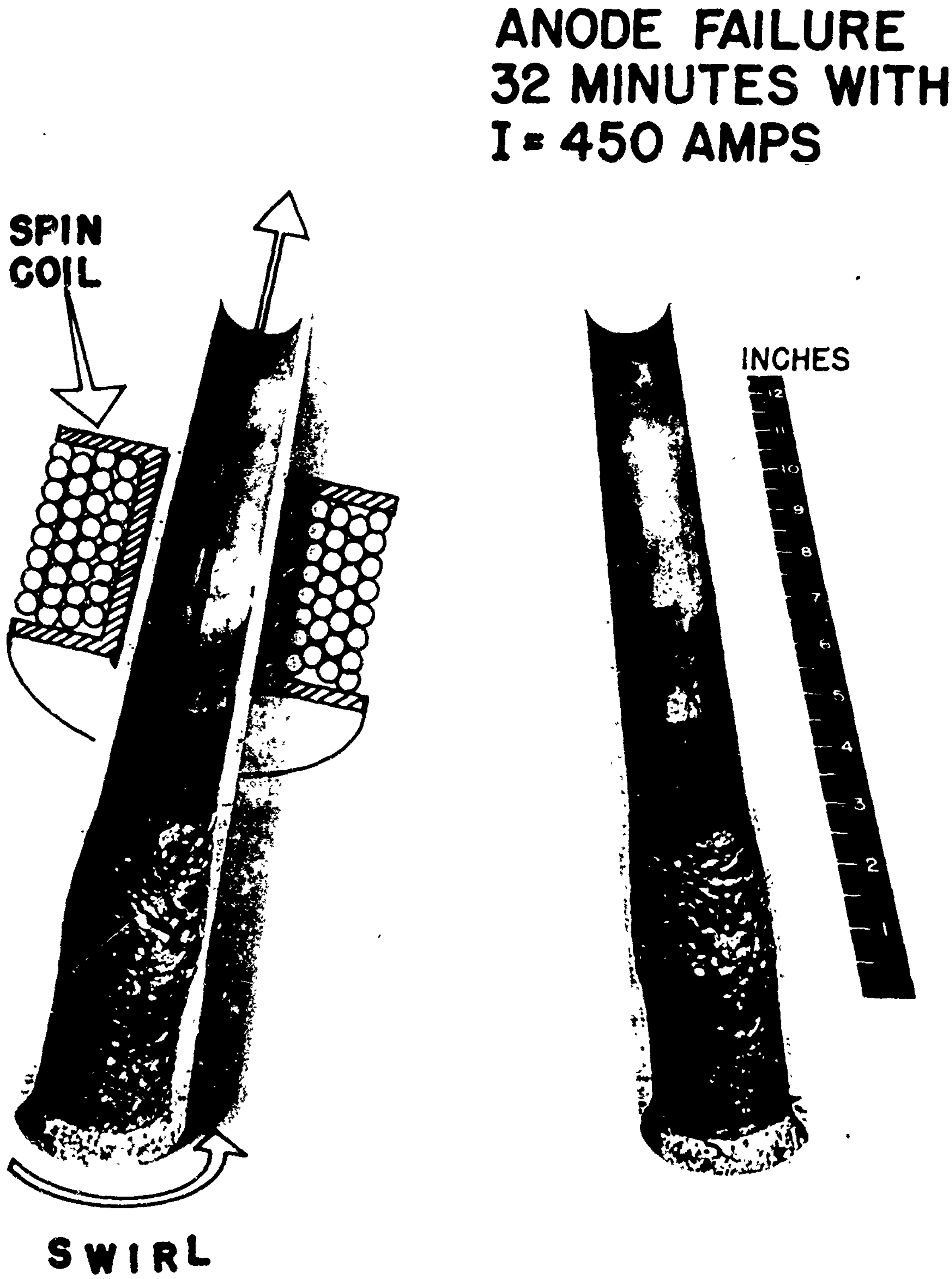


Figure 19. Rear Electrode Failure due to Normal Wear

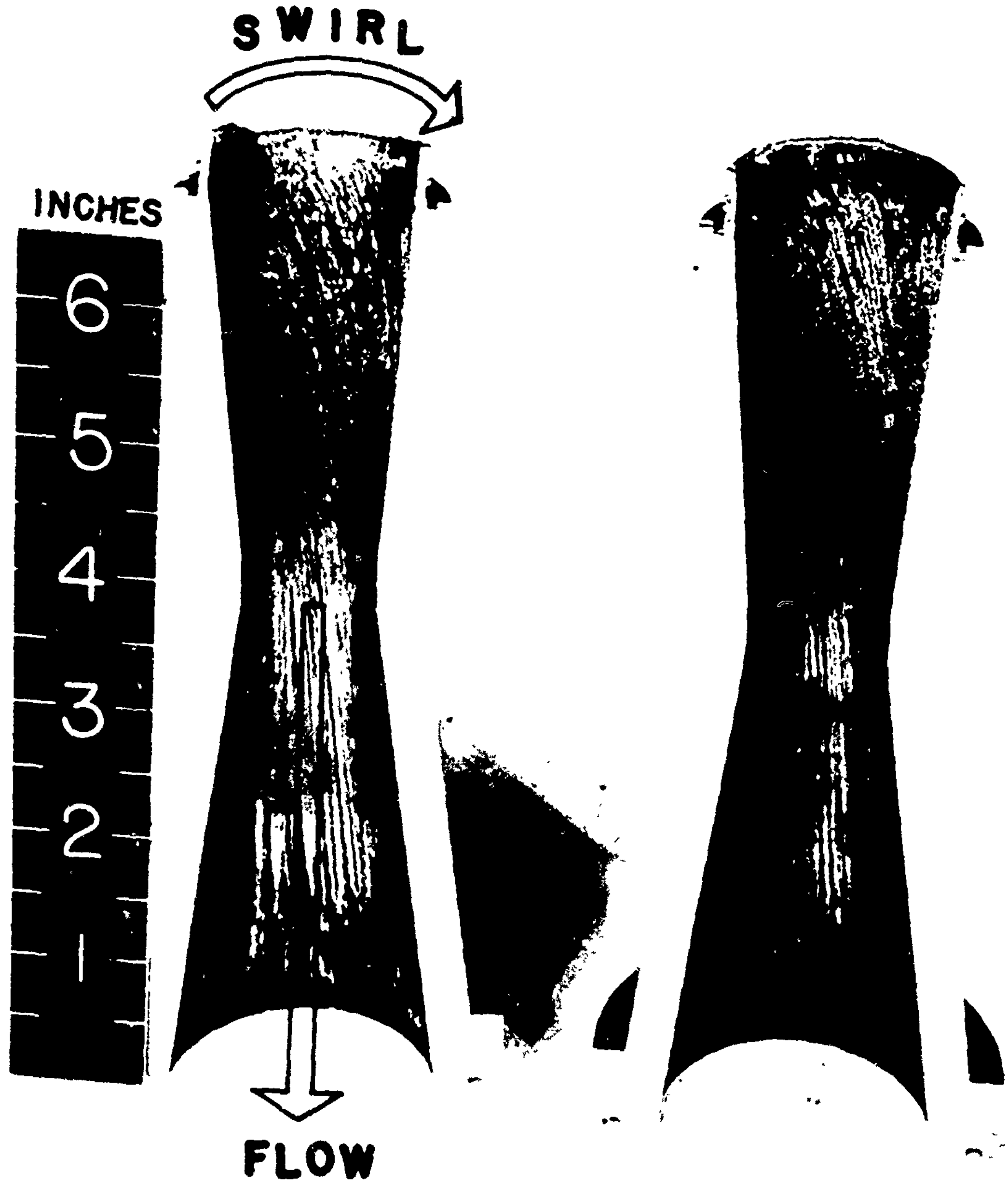


Figure 20. Nozzle Failure Due to Excess Arc Length; Swirl, Dampens During Expansion Process

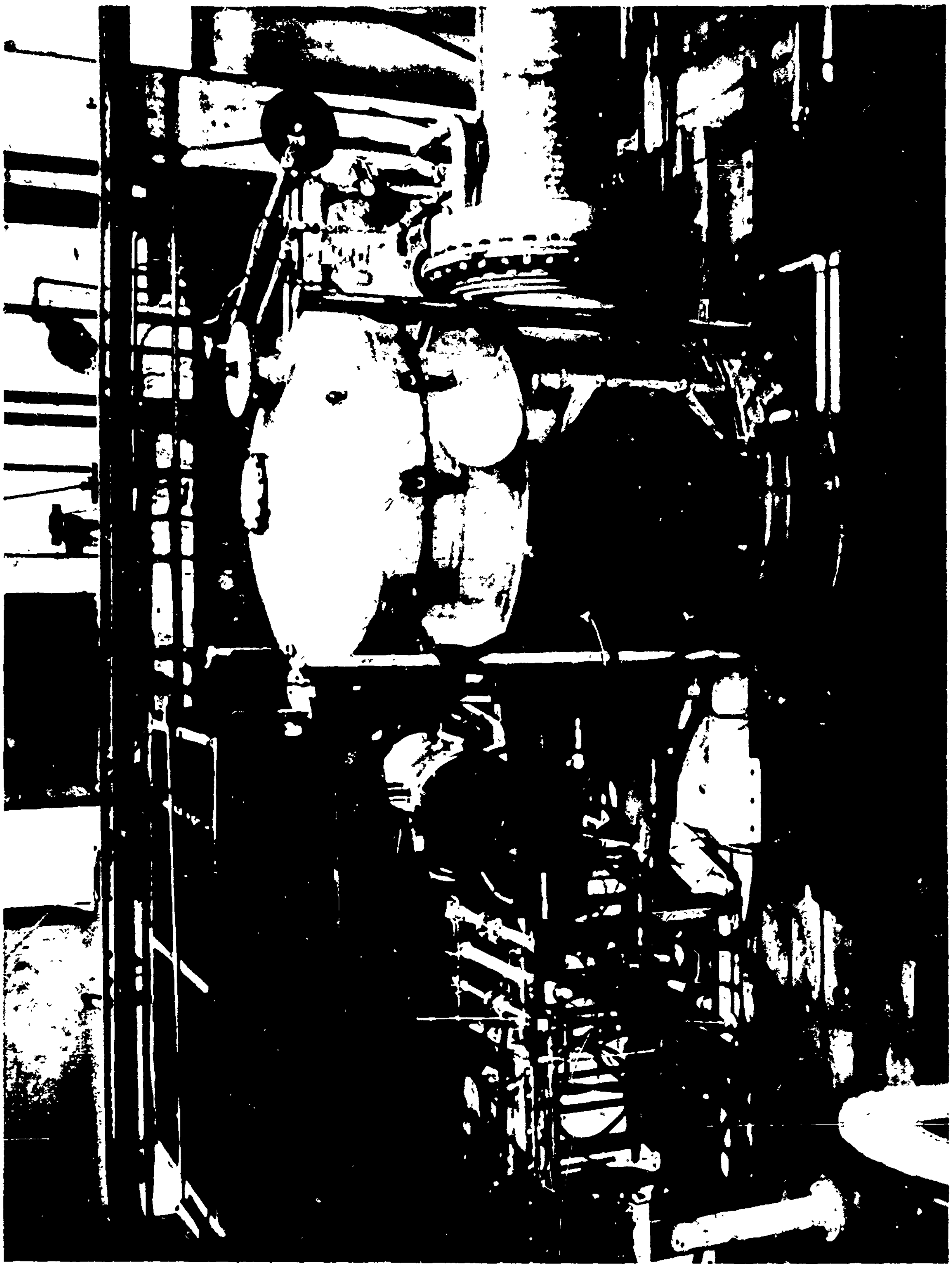


Figure 21. AFFDL 4-Megawatt Hypersonic Wind Tunnel, N=2 Arc Heater

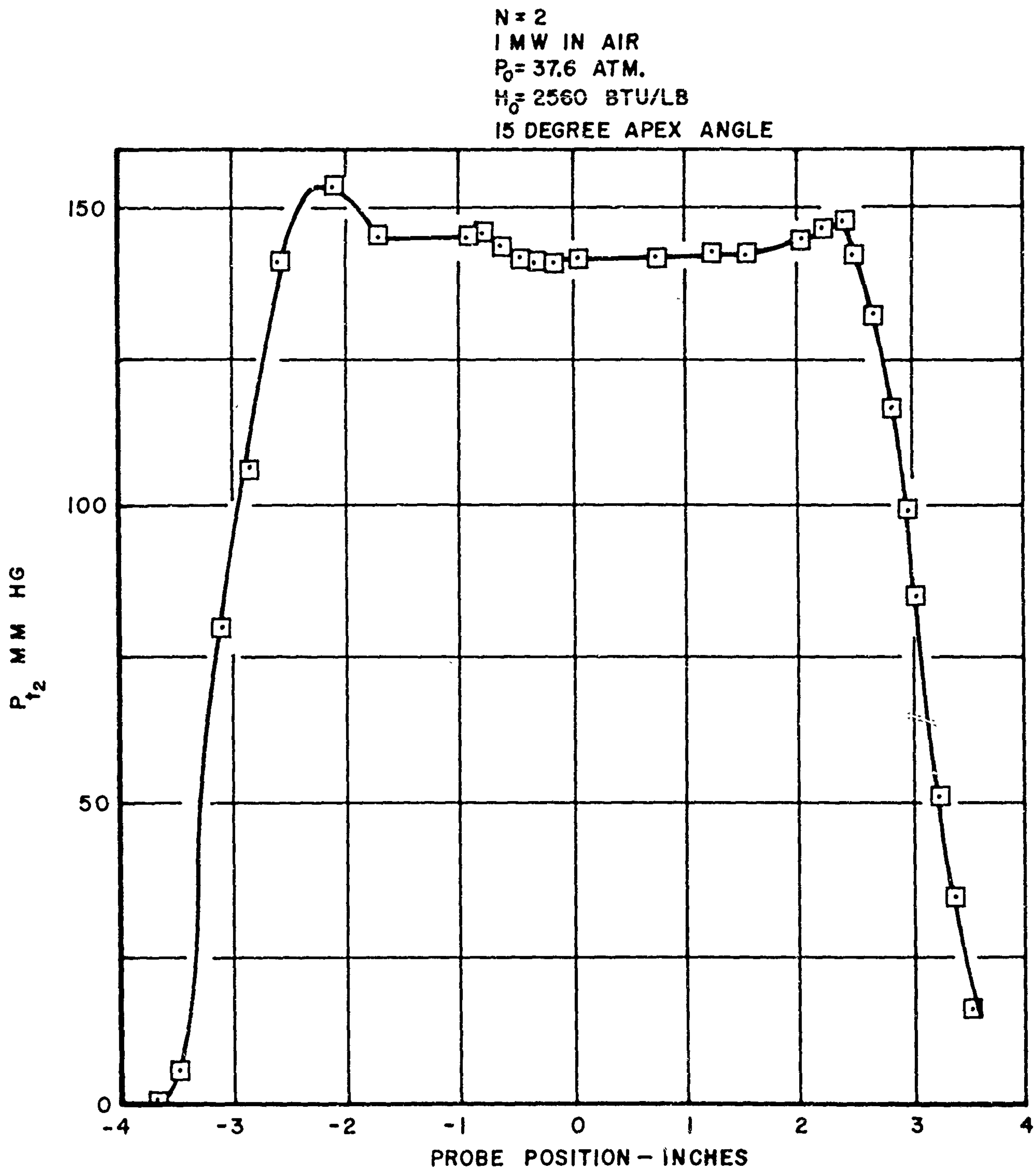


Figure 22. Typical Impact Pressure Survey Across the 7.3-Inch Conical Nozzle, 4-MW Arc Heated Hypersonic Wind Tunnel

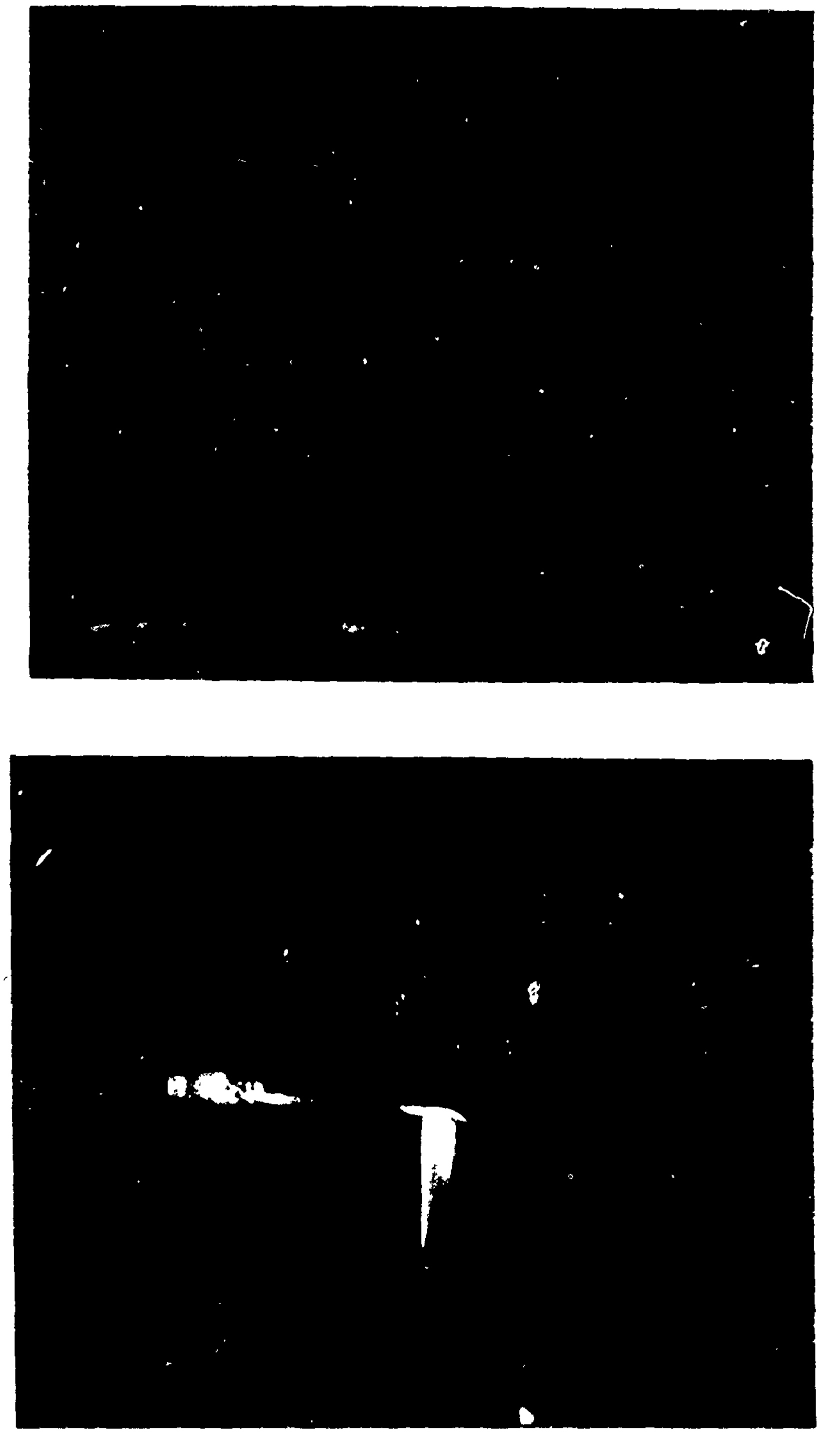


Figure 23. Impact Pressure Probe in 7.3-Inch Conical Flow of AFFDL Continuous Flow 4-MW Arc Heated Hypersonic Wind Tunnel

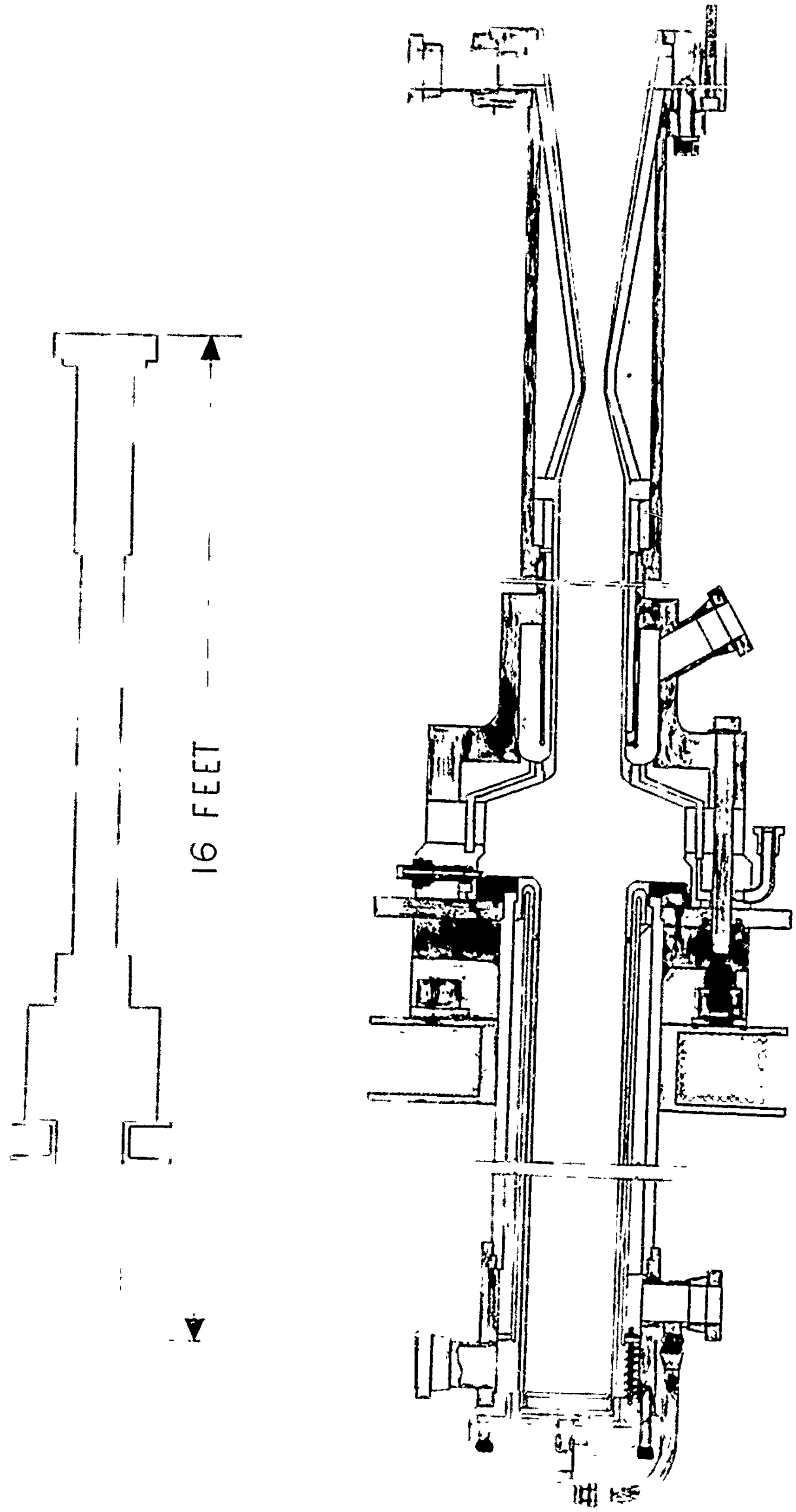


Figure 24. Schematic of AFFDL 50-MW (N=7) High-Voltage Arc Air Heater

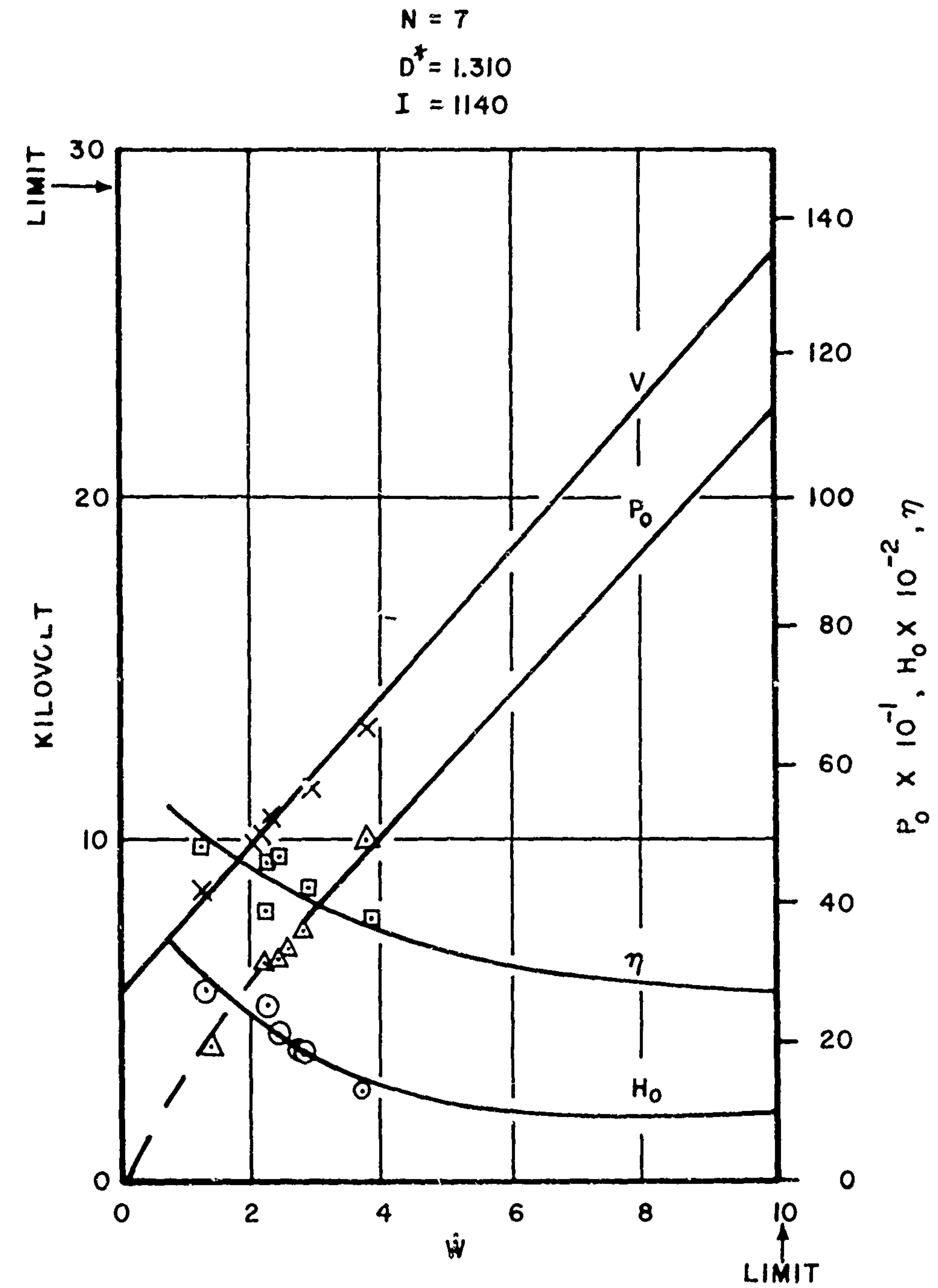


Figure 25. Scaled N=7 Data, D* = 1.310 Inches, I = 1140 Amps

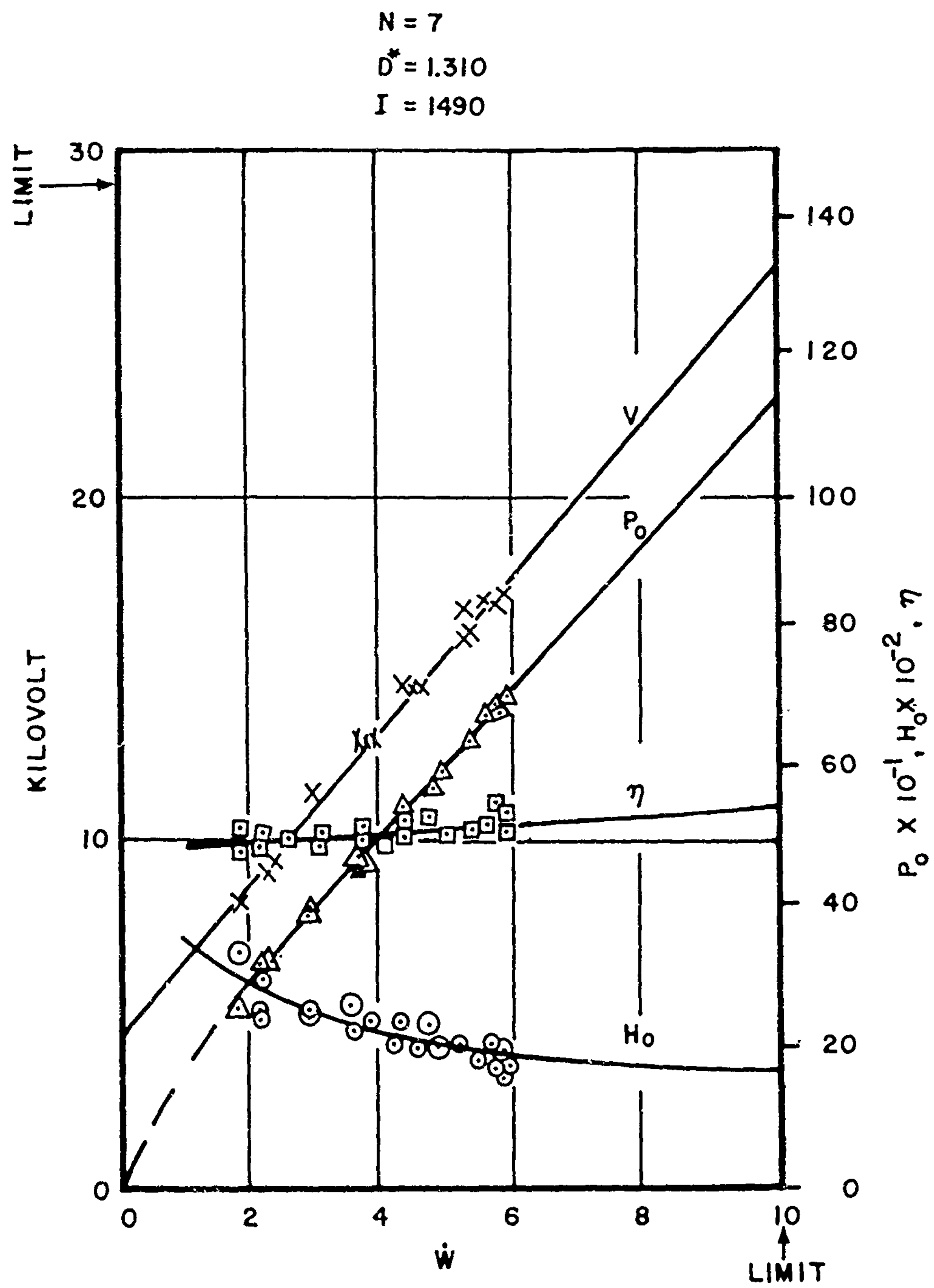


Figure 26. Scaled N=7 Data, D* = 1.310 Inches, I = 1490 Amps

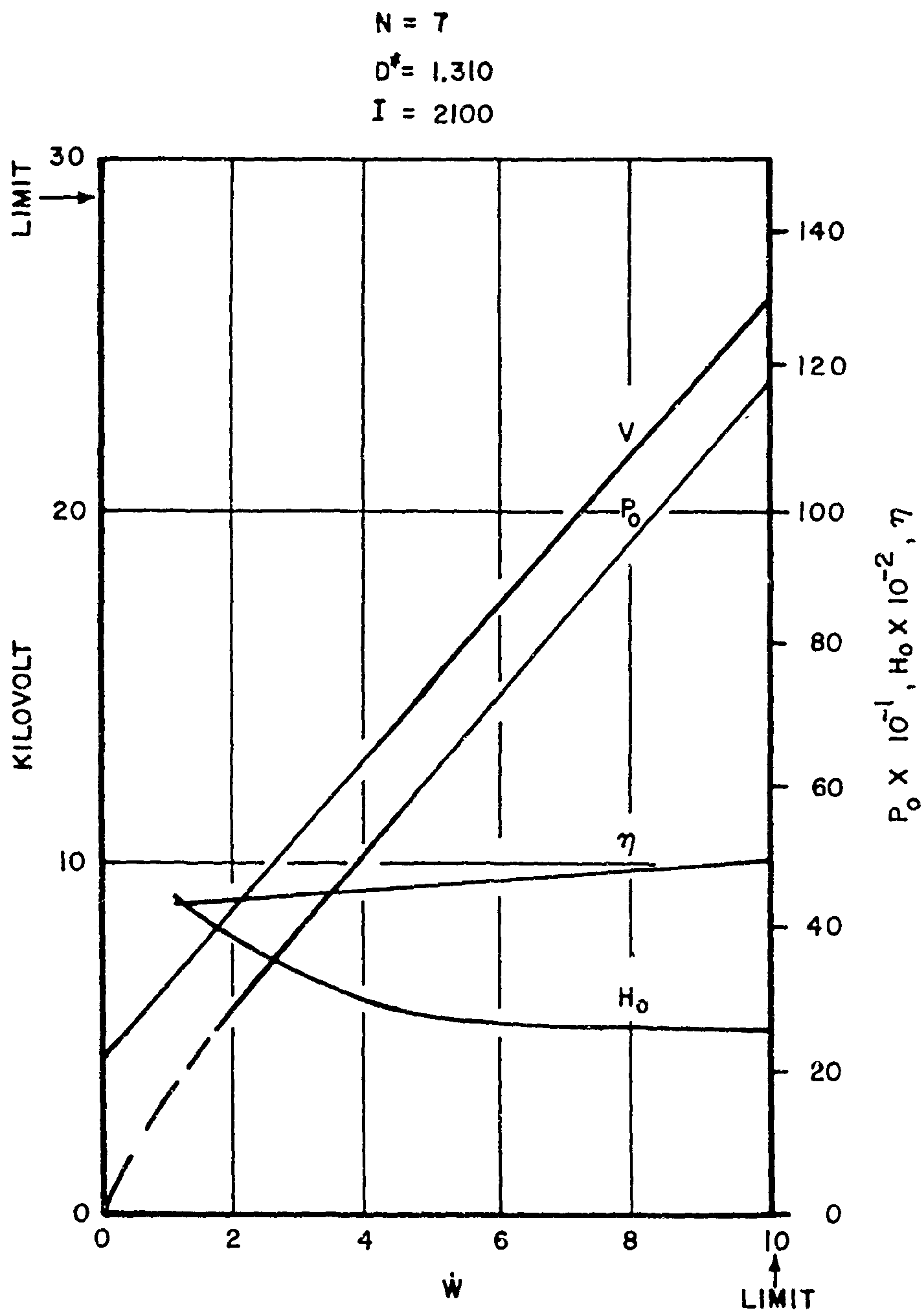


Figure 27. Scaled N=7 Data, D* = 1. 310 Inches, I = 2100 Amps

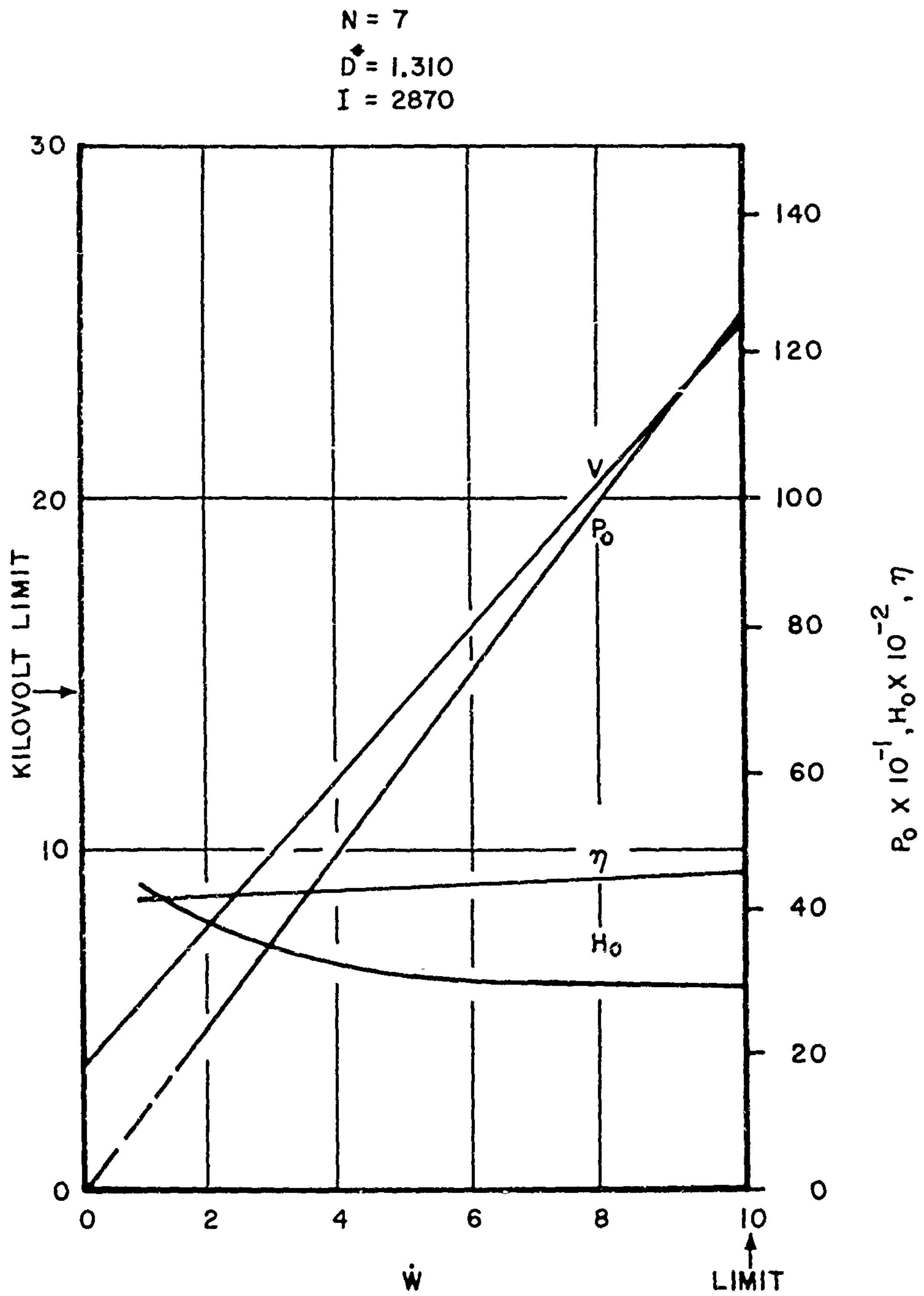


Figure 28. Scaled N=7 Data, D* = 1.310 Inches, I = 2870 Amps

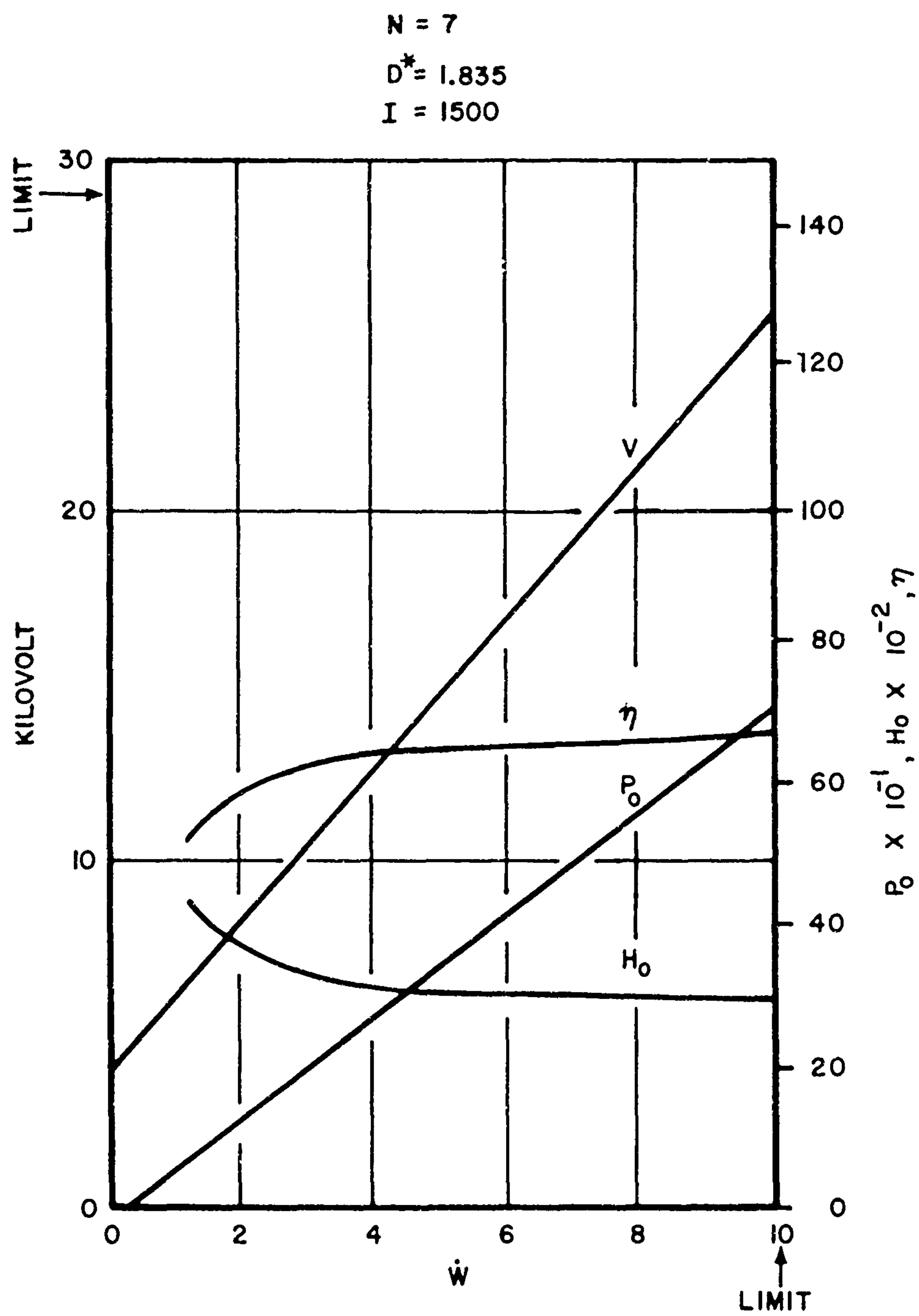


Figure 29. Scaled N=7 Data, D* = 1.835 Inches, I = 1500 Amps

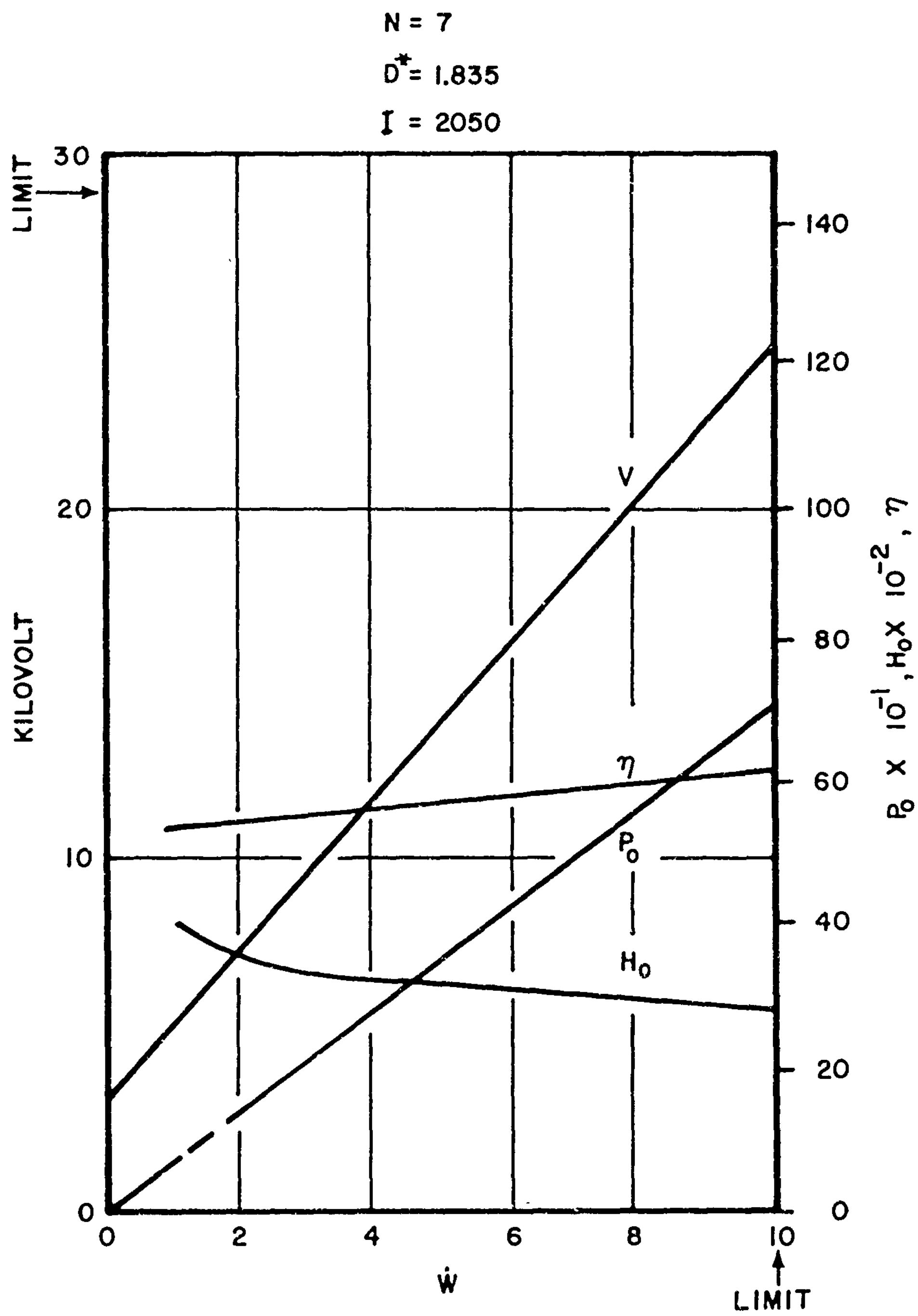
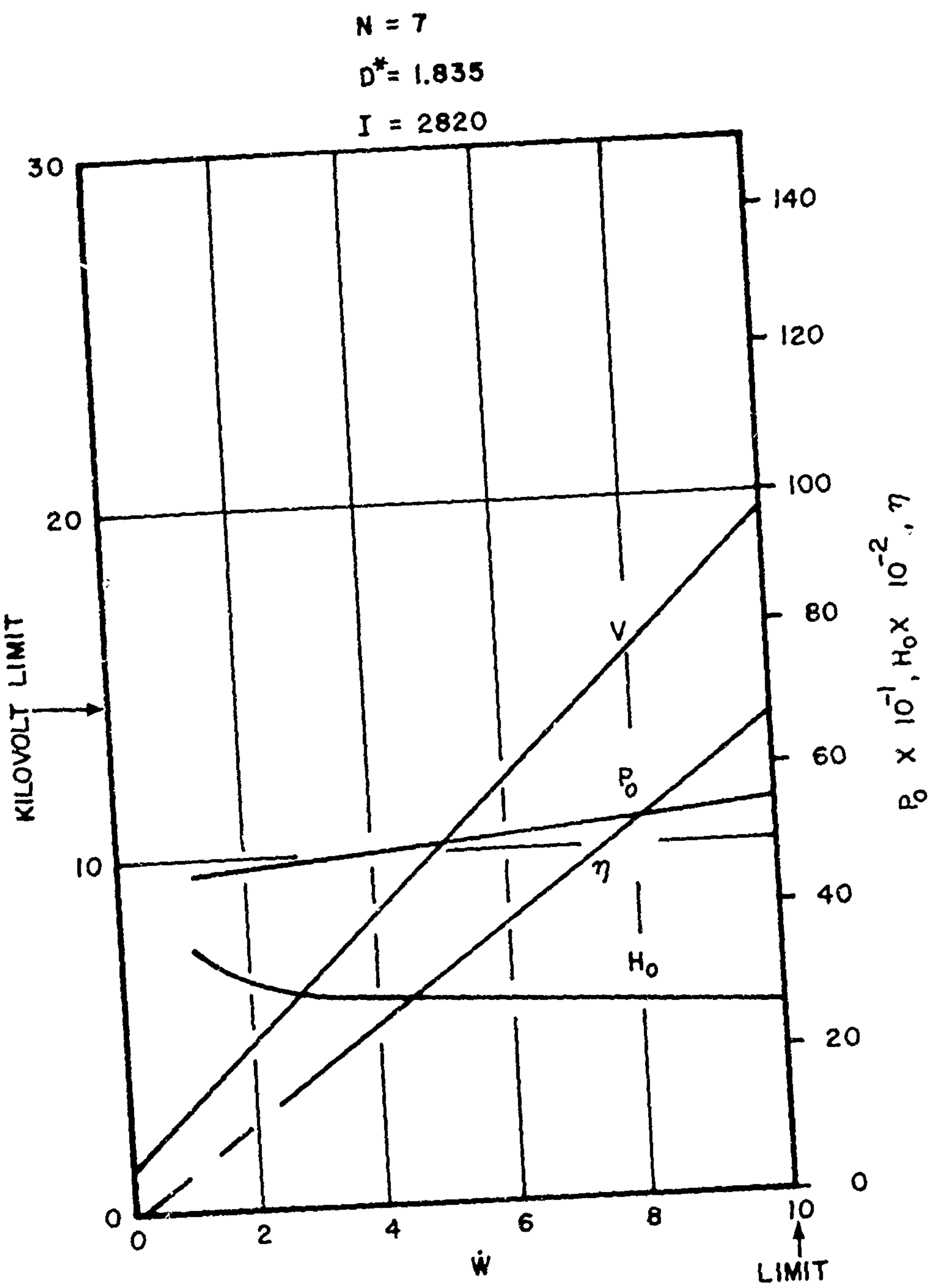


Figure 30. Scaled N=7 Data, D* = 1.835 Inches, I = 2050 Amps



NOTE:
$\dot{W}$ SHOWN ON THIS CURVE IS 20 % HIGH DUE TO FAULTY N = 2 DATA

Figure 31. Scaled N=7 Data, D* = 1.835 Inches, I = 2820 Amps

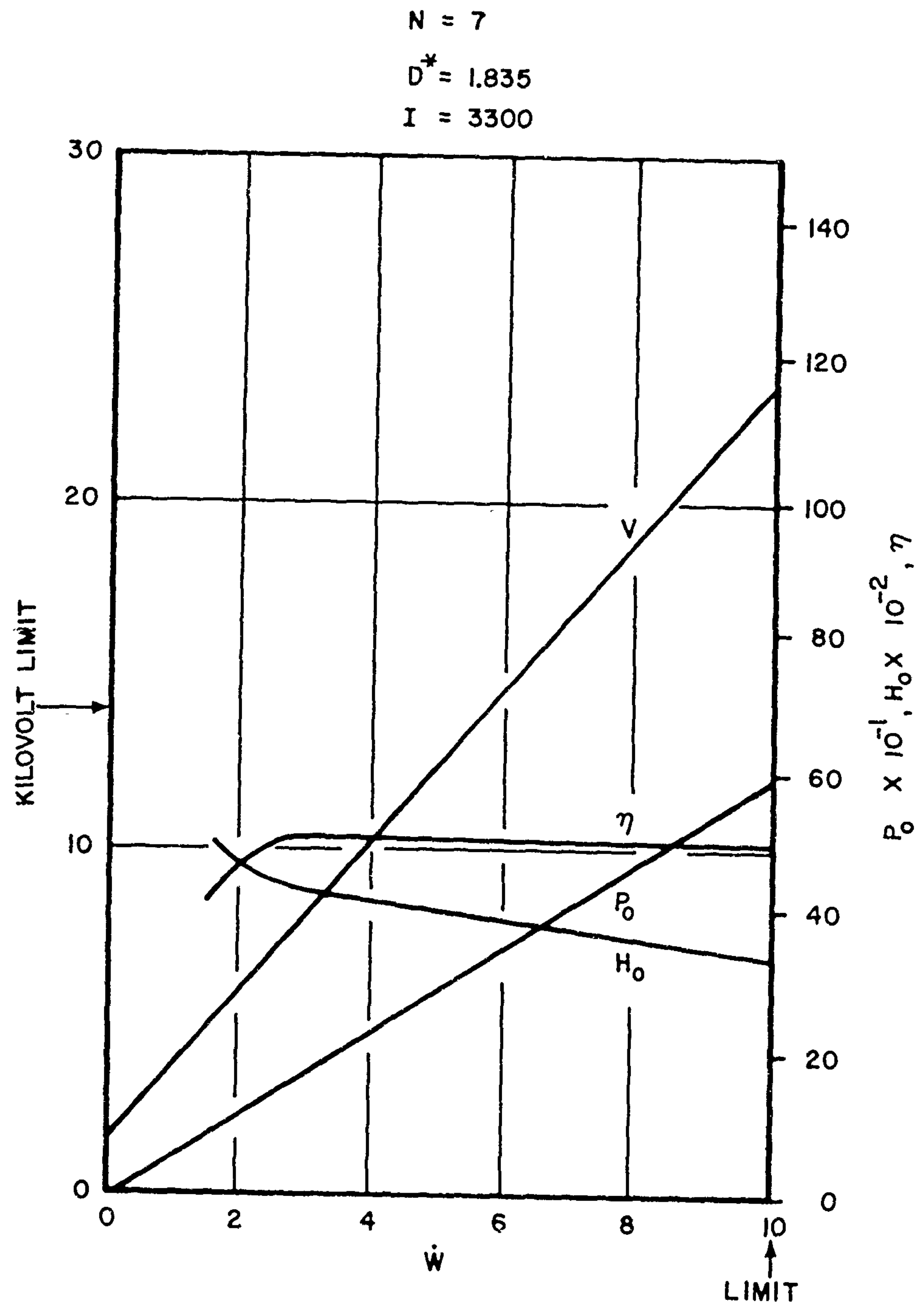


Figure 32. Scaled N=7 Data, D* = 1.835 Inches, I = 3300 Amps

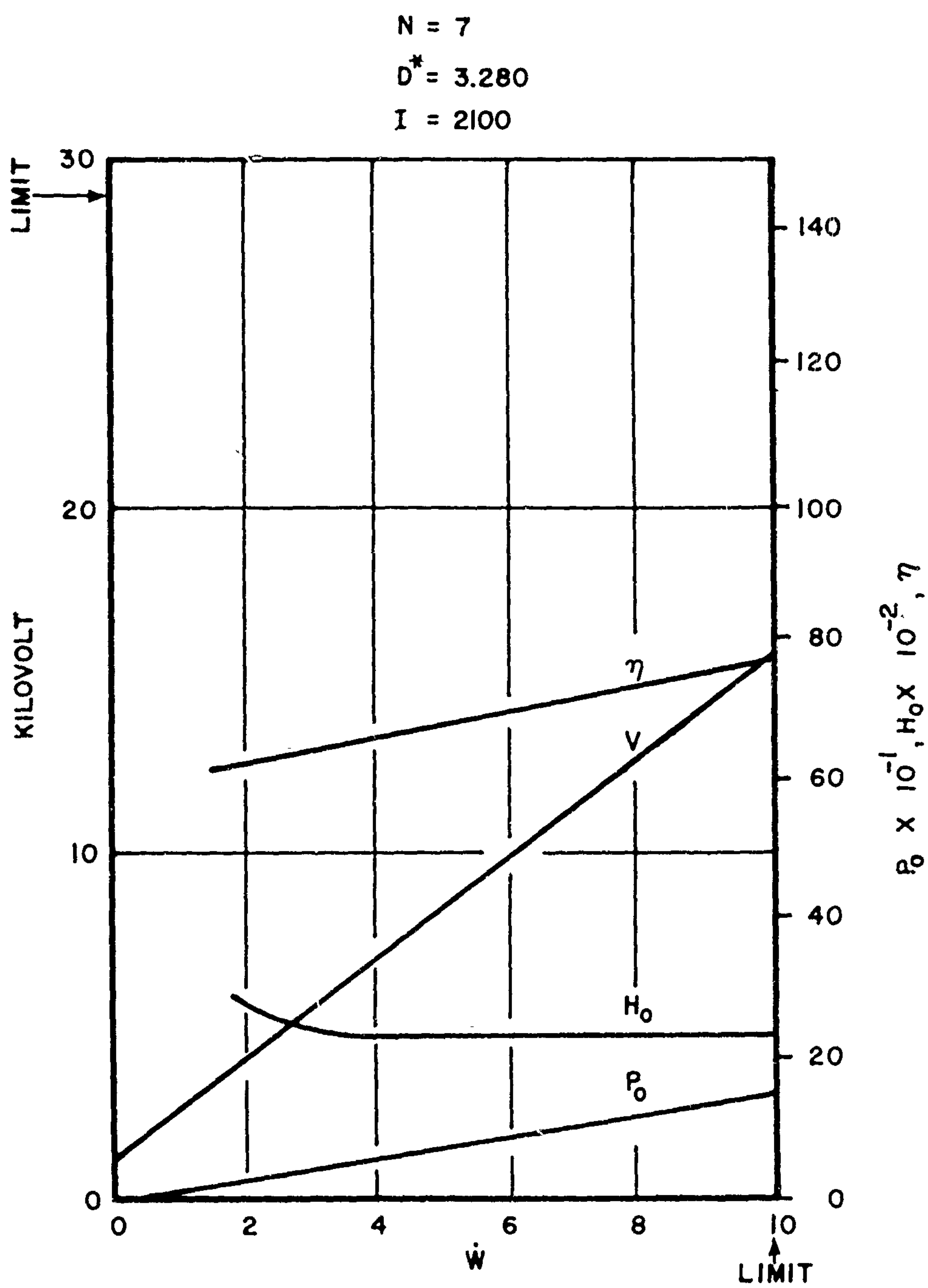


Figure 33. Scaled N=7 Data, D* = 3.280 Inches, I = 2100 Amps

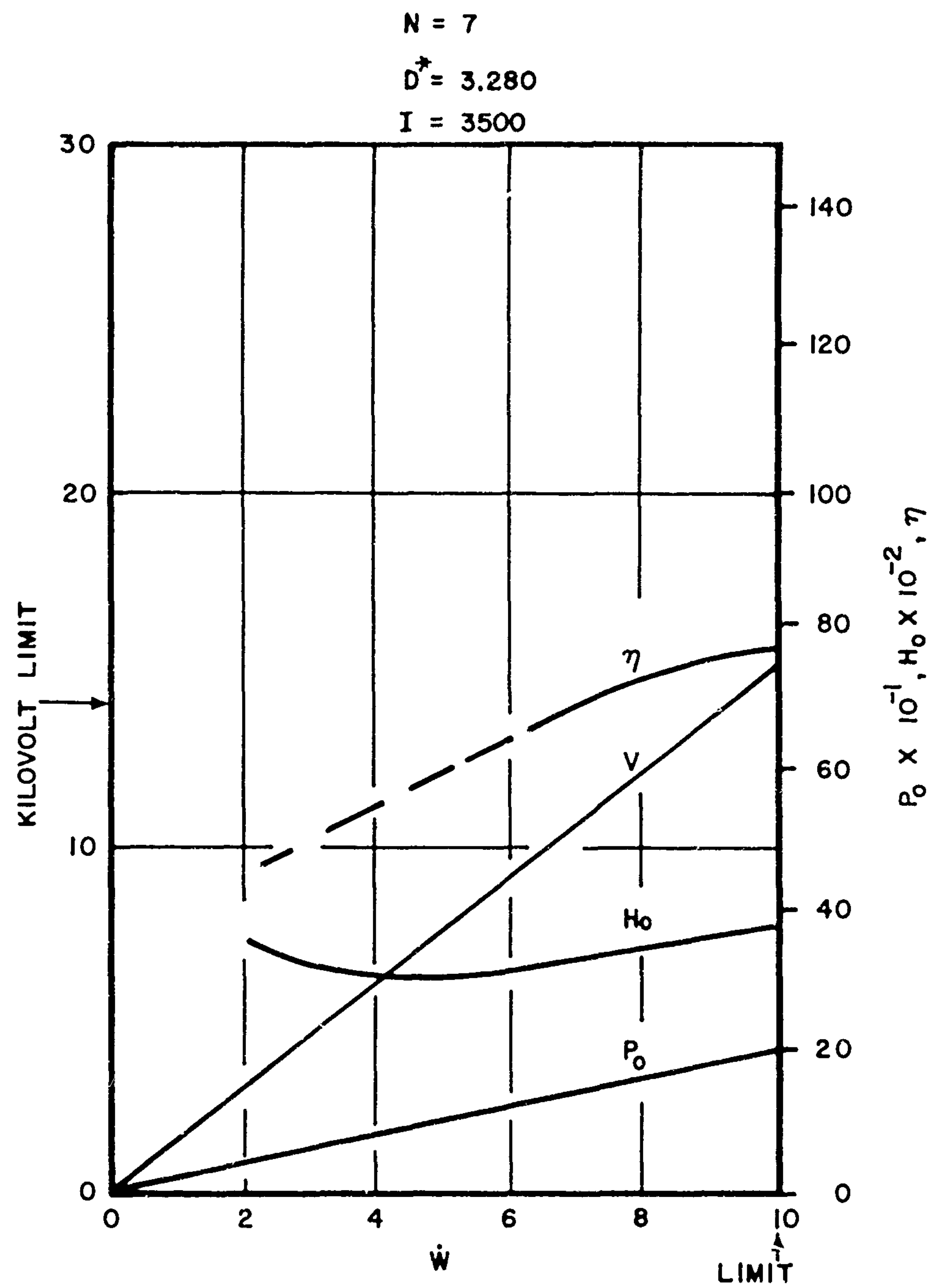


Figure 34. Scaled N=7 Data, D* = 3. 280 Inches, I = 3500 Amps

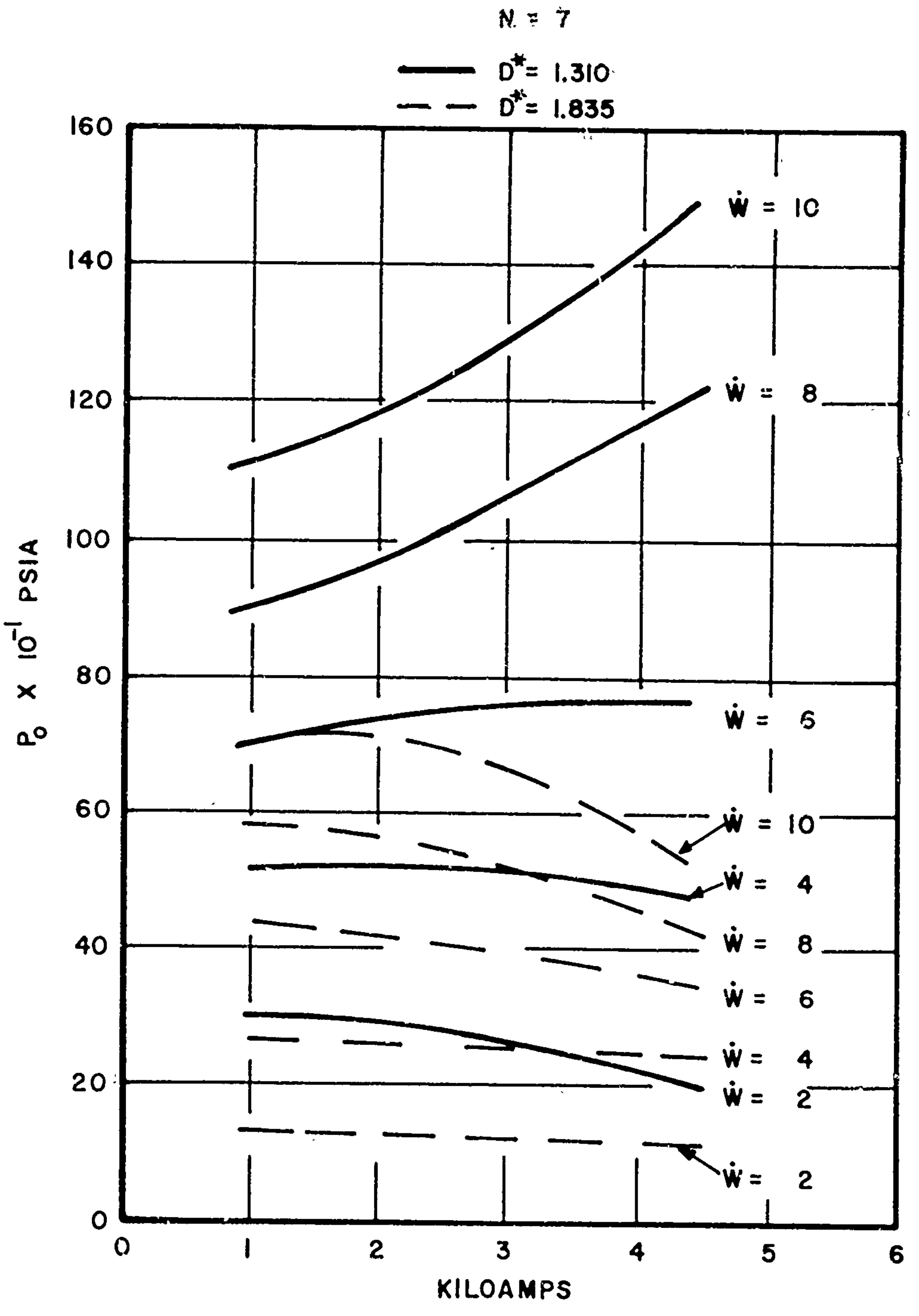


Figure 36. N=7 Stagnation Pressure - Current Summary Curve for Constant Throat Sizes

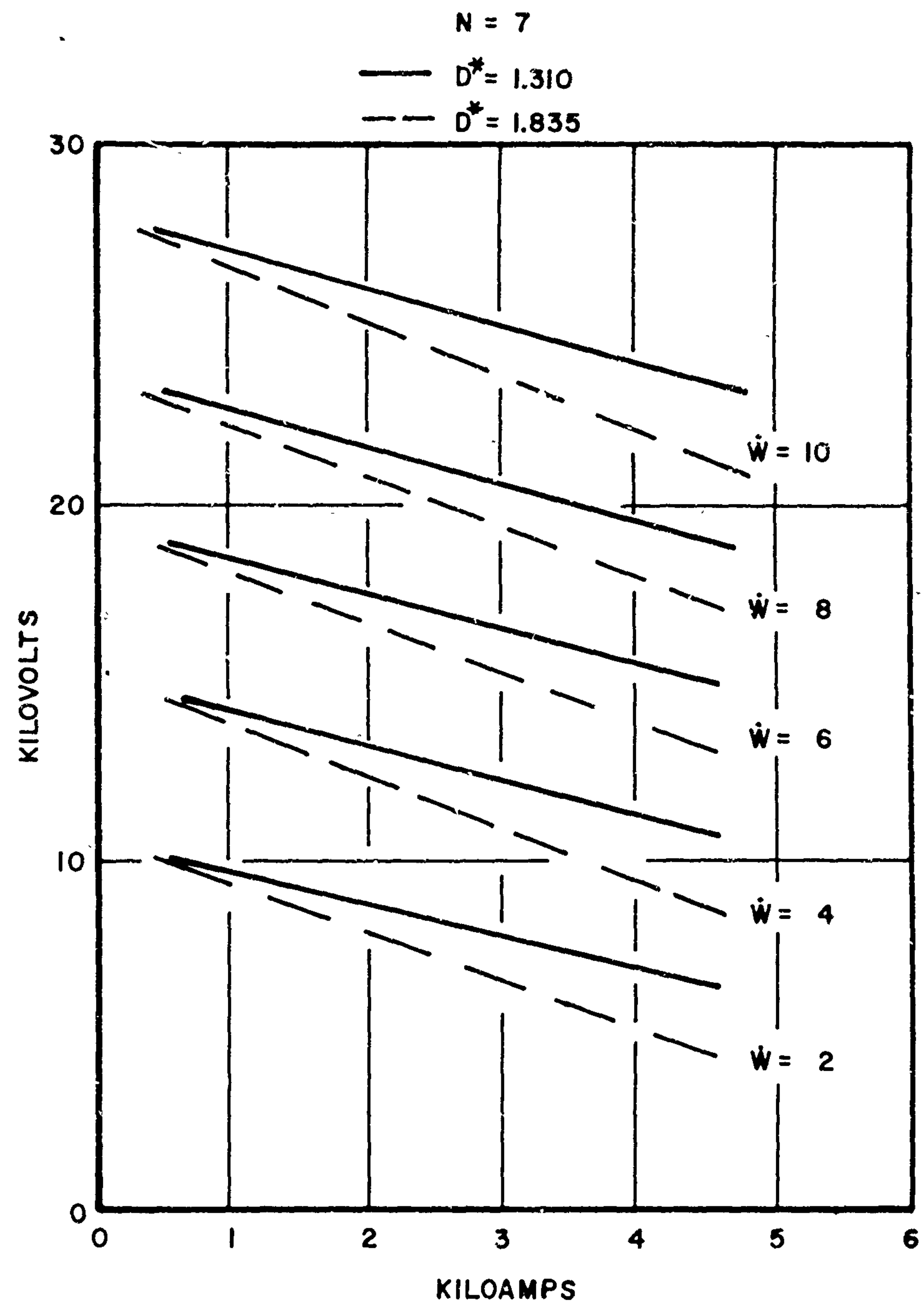


Figure 35. N=7 Voltage - Current Summary Curve for Constant Throat Sizes

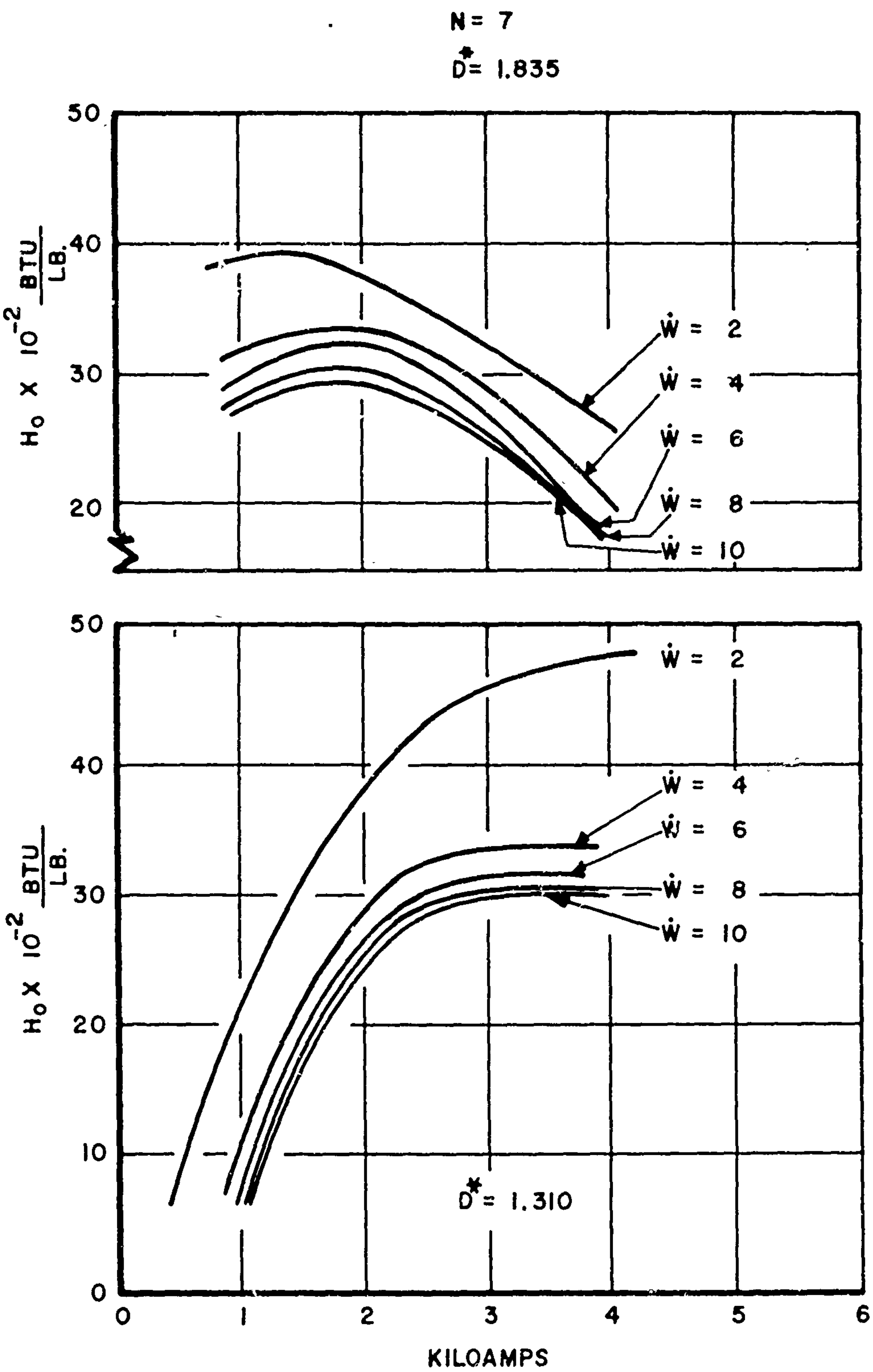


Figure 37. N=7 Bulk Stagnation Enthalpy - Current Summary Curve for Constant Throat Sizes

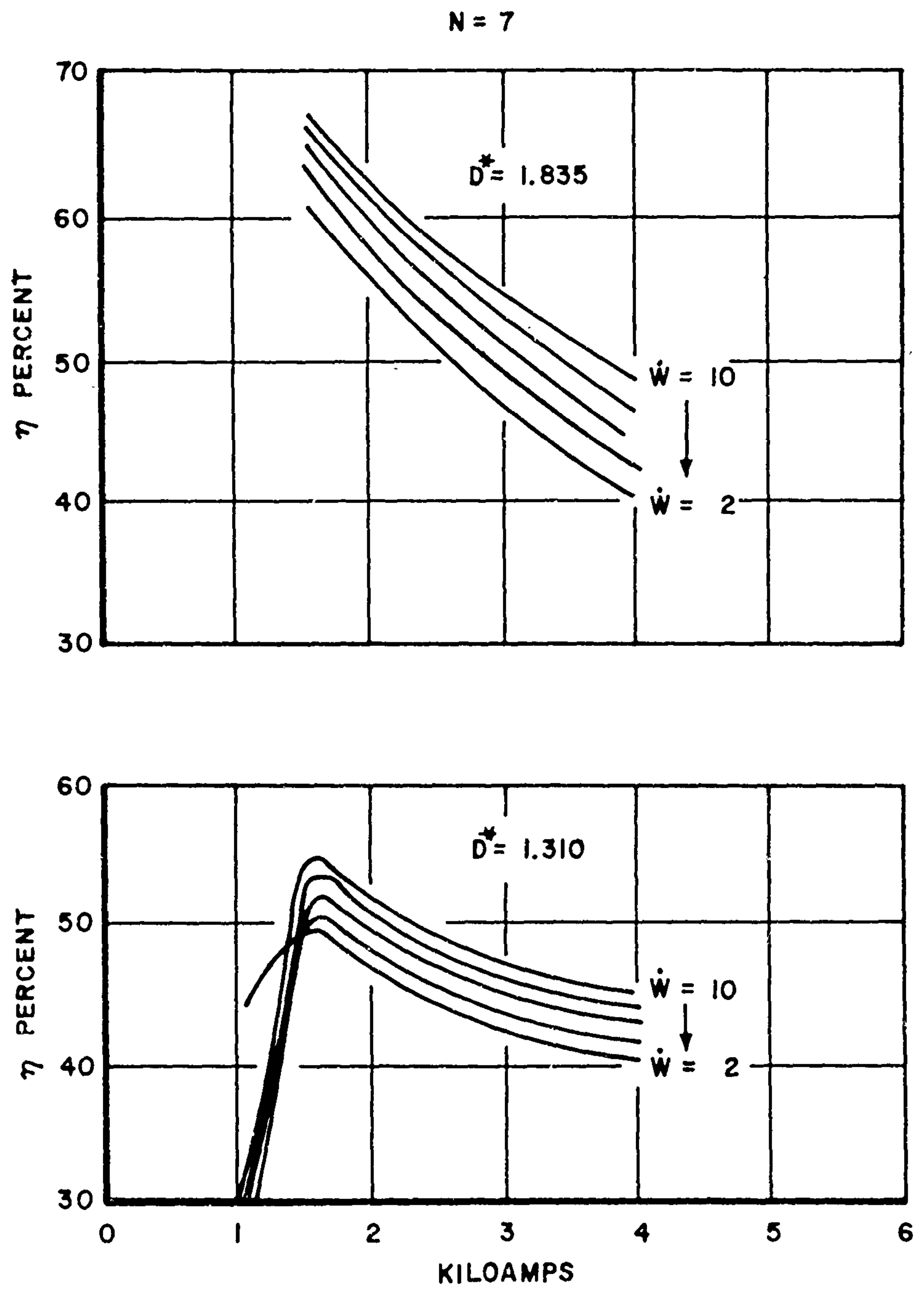


Figure 38. N=7 Air Heating Efficiency - Current Summary Curve for Constant Throat Sizes

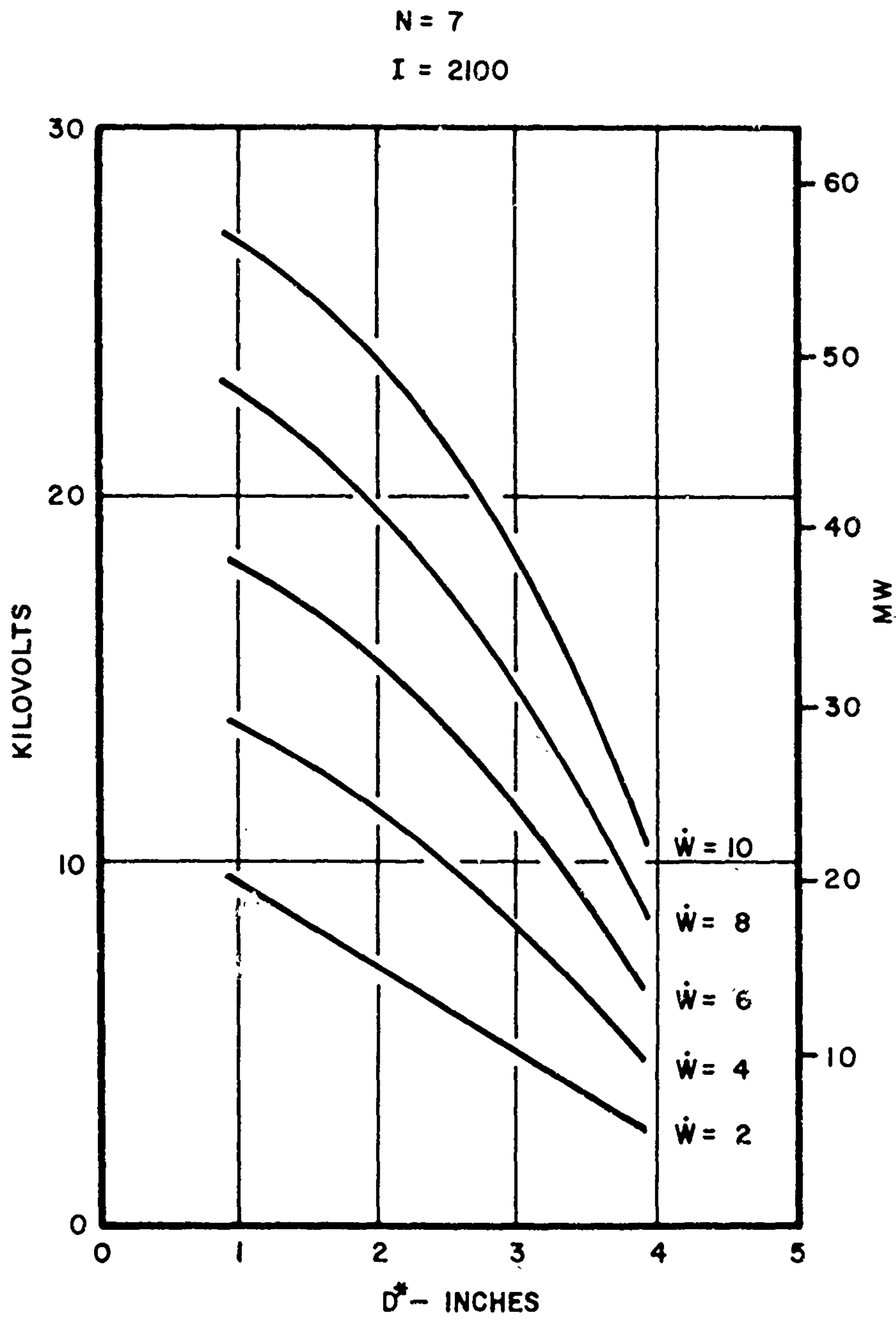


Figure 39. N=7 Voltage - Throat Diameter Summary Curve for Current of 2100 Amps

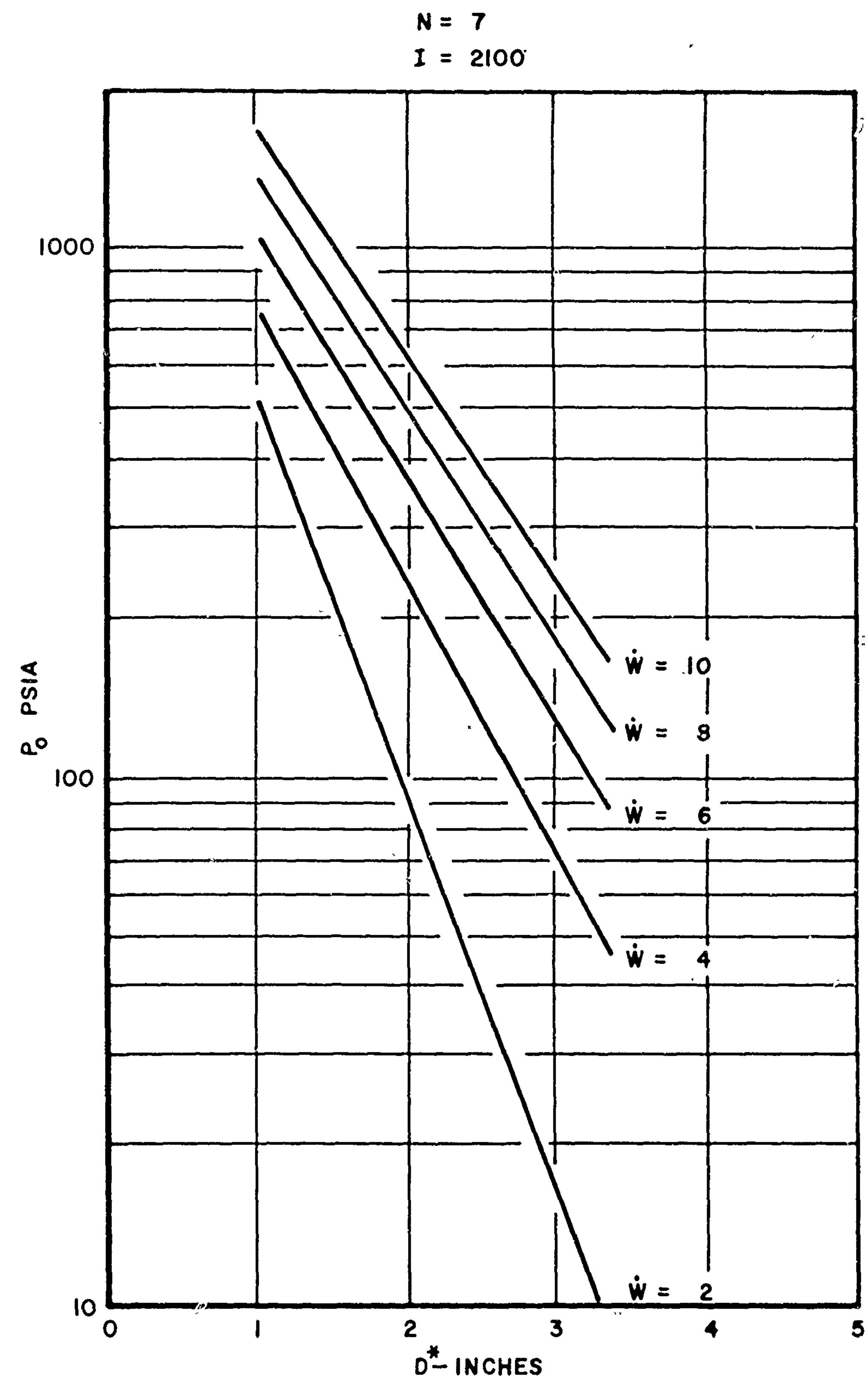


Figure 40. N=7 Stagnation Pressure - Throat Diameter Summary Curve for Current of 2100 Amps

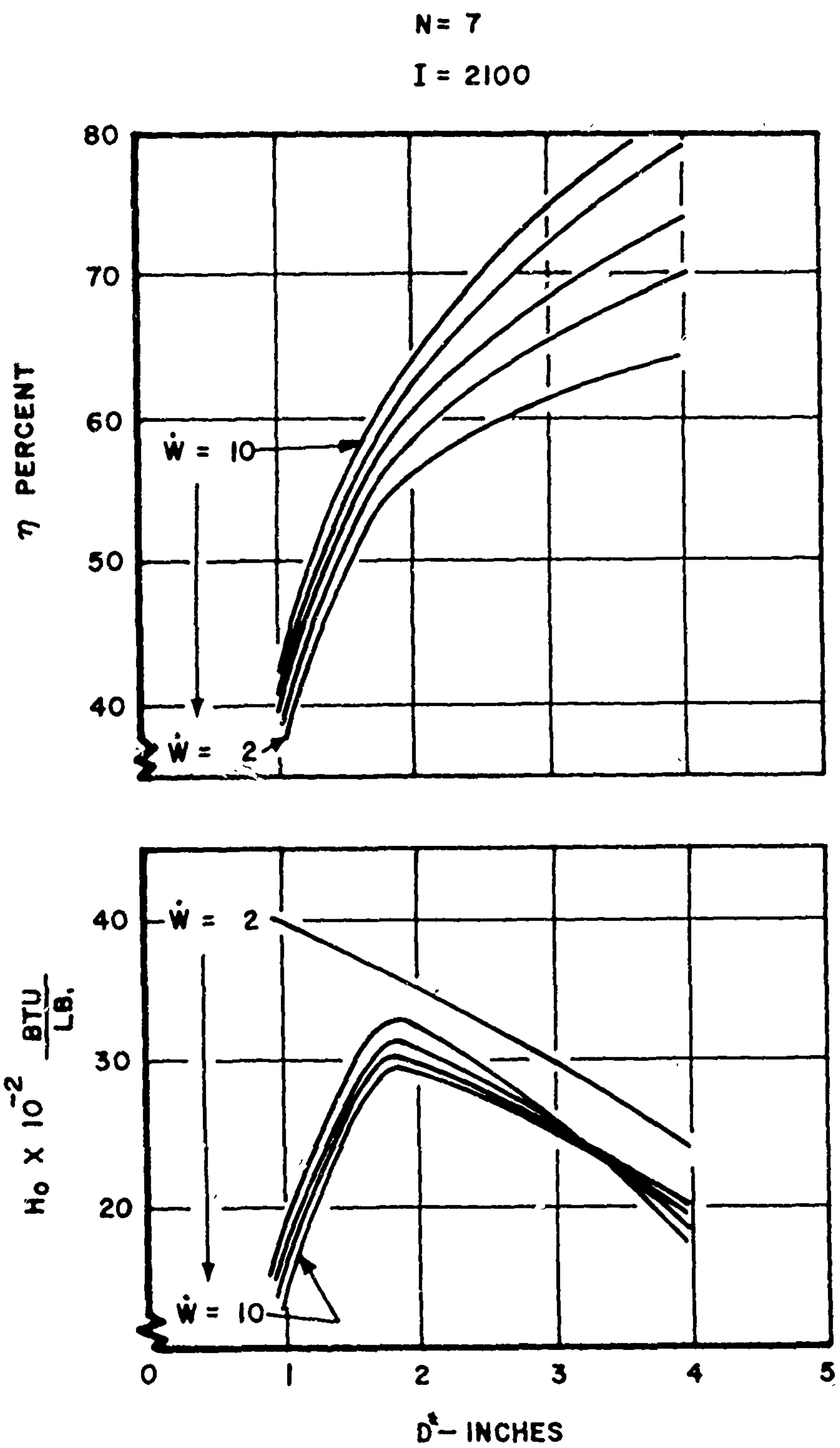


Figure 41. N=7 Bulk Stagnation Enthalpy and Air Heating Efficiency - Throat Diameter Summary Curve for Current of 2100 Amps

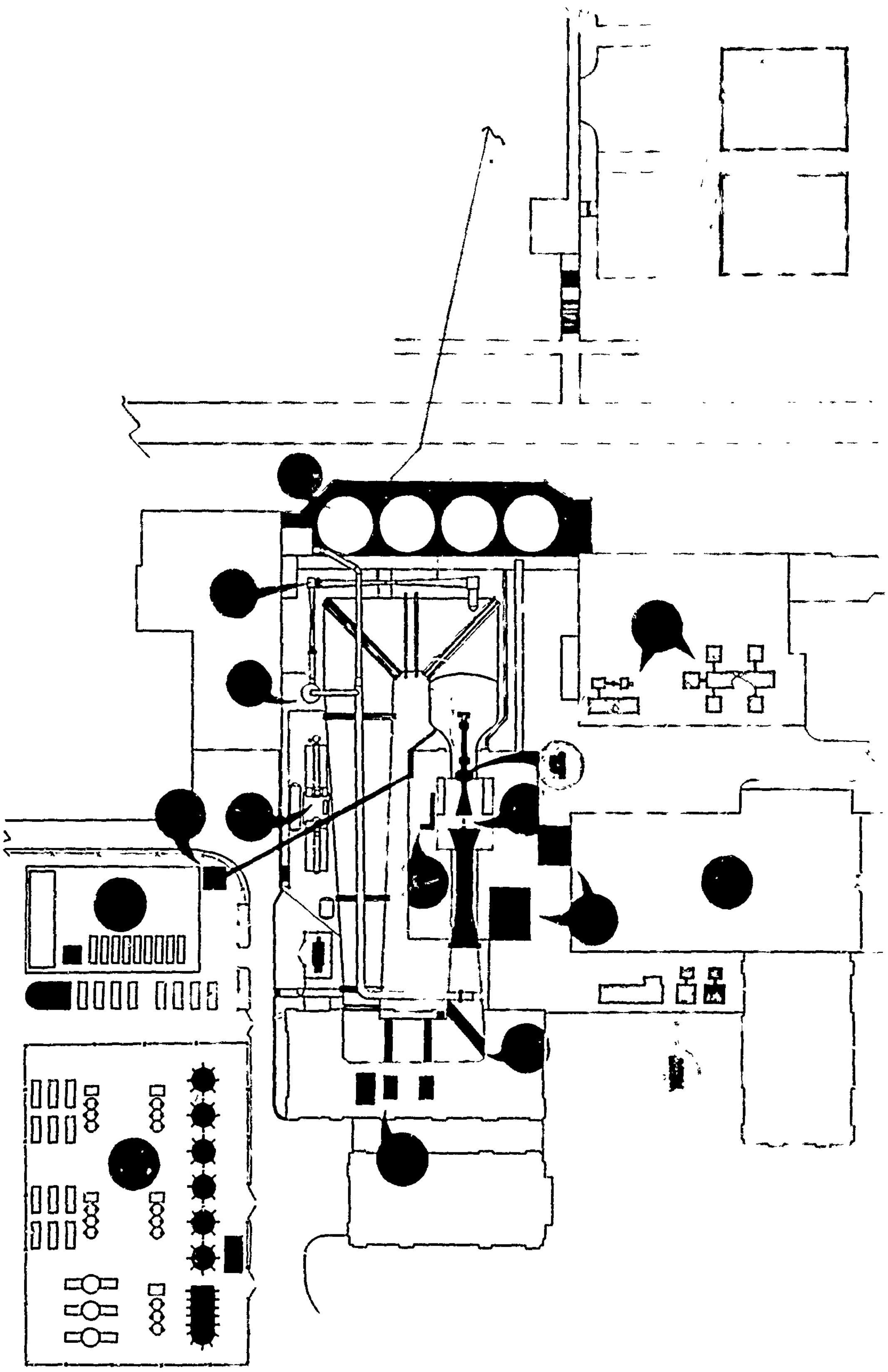


Figure 42. Schematic of the 50-MW Facility Showing Major Components